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Publication date:
1992

Document Version
Publisher's PDF, also known as Version of record

RISØ

Risø-R-641(EN)

Methodology for Justification and Optimization of Protective Measures Including a Case Study:

Protective Actions Planned for Gotland in an »EXERCISE SIEVERT«-Release

Prepared by a Working Group

Risø National Laboratory, Roskilde, Denmark
July 1992

BER-3.2 Report: Methodology for Justification and Optimization of Protective Measures Including a Case Study:

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Protective Actions Planned for Gotland in an »EXERCISE SIEVERT«-Release

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July 1992

Abstract This report is a part of the Nordic BER-3 project's work to propose and harmonize Nordic intervention levels for countermeasures in case of nuclear accidents.

This report focuses on the methodology for justification and optimization of protective measures in case of a reactor accident situation with a large release of fission products to the environment.

The down-wind situation is very complicated. The dose to the exposed society is almost unpredictable. The task of the radiation protection experts: To give advice to the decision makers on averted doses by the different actions at hand in the situation - is complicated. That of the decision makers is certainly more: On half of the society they represent, they must decide if they wish to follow the advices from their radiation protection experts or if they wish to add further arguments - economical or political (or personal) - into their considerations before their decisions are taken.

Two analysis methods available for handling such situations: **cost-benefit analysis** and **multi-attribute utility analysis** are described in principle and are utilized in a case study: The impacts of a Chernobyl-like accident on the Swedish island of Gotland in the Baltic Sea are analyzed with regard to the acute consequences.

The use of the intervention principles found in international guidance (IAEA 91, ICRP 91), which can be summarized as the principles of **justification, optimization and avoidance of unacceptable doses**, are described.

How to handle more intangible factors of a psychological or political character is indicated.

NKS Project BER-3
Evaluation and harmonization of the planning of countermeasures and the use of intervention levels

ISBN 87-550-1825-4
ISSN 0106-2840

Grafisk Service, Risø, 1992

Contents

1 Introduction

In a reactor accident situation like the scenario described in this report, where a very large release of mixed fission products is assumed to have taken place, the situation for the down-wind radiation protection experts and the competent decision makers is very complicated.

They face a situation, where the dose to the exposed society is almost unpredictable. The major component of dose can be expected from inhalation, and as the deposition dose will be strongly dependent on eventual rain, a forecast of the deposition dose component will be as uncertain as the weather forecast.

In the primary phase, where only few - if any - information are available, the first practical indicators, such as the first measurements of outdoor dose rates, are not directly applicable and have to be judged very carefully for many reasons.

In the later phases, when the stream of information can be overwhelming and its interpretation be complicated, the situation is however more stable and opens for more detailed analysis and clearer advices.

The task of the experts: To give advice to the decision makers on averted doses by the different actions at hand in the situation - is complicated. That of the decision makers is certainly more: On behalf of the society they represent, they must decide if they wish to follow the advices from their radiation protection experts or if they wish to add further arguments - economical or political (or personal) - into their considerations before their decisions are taken.

Such Arguments Must be Transparent to the Society.

The aim of the BER-3 project is to propose and harmonize Nordic intervention levels for countermeasures in case of nuclear accidents.

As a step in this work and in order to promote the understanding of the complicated situation described above, this report presents a case study to evaluate intervention level settings by two methods available for handling such situations: **cost-benefit analysis and multi-attribute utility analysis.**

The scenario for the case study has been chosen from the drill performed by the Swedish National Institute of Radiation Protection (SSI) on December 5 and 6 1990: EXERCISE SIEVERT.

In this drill an accidental release following a hypothetical accident at the nuclear power plant Ignalina with a release of fission products to the atmosphere was assumed to have hit South-eastern Sweden incl. the islands of Gotland and Öland.

For the purpose of the present study it was chosen to limit the analysis to the possible impact on the island of Gotland in the Baltic Sea.

It was also chosen to concentrate upon the acute protective measures and leave the longer term problems such as food restrictions and agricultural measures.

The Accident scenario is described in Section 2. Accident consequences are described in Section 3, the effects and costs of protective measures in Section 4.

The purpose of this study is further to demonstrate for Nordic conditions the use of the intervention principles found in international guidance (IAEA 91, ICRP 91). These can be summarized as the principles of **justification, optimization and avoidance of unacceptable doses,** i.e. doses causing deterministic effects.

Intervention levels which are based on radiation risk reduction and associated cost form the basis of the inputs to the decision making process from the radiation protection community. The input from the radiation protection community to the decision making process should be published separately to ensure transparency to the public.

An accident itself and the introduction of protective action entails health risks to the people affected, monetary cost and social disruption. The protective action, often including objectives which are difficult to control simultaneously, cannot be undertaken without careful contemplation and consideration of the essential consequences of decisions. Decision analysis is an appropriate methodology assisting in rendering explicit and apparent all factors involved and in evaluating their relative importance for the decision maker.

Different decision aiding techniques are available for the decision maker e.g. multi-attribute utility analysis, cost benefit analysis, interactive multi-objective programming and analytical hierarchy process.

Section 5 gives an introductory description of two quantitative decision-aiding techniques: cost-benefit analysis and multi-attribute utility analysis.

In Section 6 is described the justification and optimization of protective measures found by the two above mentioned methods.

Finally in Section 7 the conclusions of the present case study are summarized.

In this case study it was decided that a central alpha value, »the price of one manSv« of 20.000 US $/manSv , should be used i the calculations and that sensitivity of this choice should be tested by increasing and decreasing this value by factors of 5 and 20 respectively.

The numerical values for the various quantities have been chosen only for the purpose of demonstrating the methodologies.

They should not be considered as recommended values.

At several occations in the process provisional results have been presented by the working group to an extended forum called the »Authority Group«: The working group supplied with the following persons from the Nordic radiation protection authorities:

Jan Olof Snihs , SSI, Stockholm,
Thorolf Bertelsen, SIS, Oslo and
Hugo Simonsen, SIS, Copenhagen.

Sigurður Magnusson, Reykjavik has been informed of the work.

The discussions have led to substantial improvements of the work and the working group wish to thank the above mentioned persons for their participation.

2 Accident Scenario

A Chernobyl-like accident is assumed to have happened at the nuclear power plant in Ignalina, Lithuania on June 16th at 20.00 including a fire in the core.

The following fractions of the total core inventory are assumed to have been released to the atmosphere by the accident:

Noble gases	100 %
Iodines	40 - 60 %
Tellurium	20 %
Cesium	30 %
Others	5 %

Weak easterly winds are prevailing in the area of Gotland. According to meteorological forecasts no fall-out can be expected before June 17th at about 17.00 on the island of Gotland.

Furthermore it is expected that the passage of the radioactive plume will last for around 15 hours from 17.00 to 08.00 on June 18th. A »cold front« passage is expected to give heavy showers/thunder over Gotland during the night. This will deposit a large part of the radioactive material in the plume as wet fall-out on the ground. In this report it is assumed that there will be no significant fallout on the Swedish mainland or later on on Gotland. The mainland contamination is set to one tenth of that on Gotland.

The island of Gotland has a total of 56,000 inhabitants. The number of children below the age of 14 years is around 10,000. The number of pregnant women is expected to be around 500. The town of Visby on the east-coast has 20,500 inhabitants.

3 Accident Consequences

3.1 External and Internal Doses in the Primary Phase

When decisions of possible protective actions are to be taken on June 17th between 08.00 and 15.00 no detailed information (except weather forecasts) on the plume passage and the resulting doses is available. The average individual (effective) dose to people staying outdoors during the 15 hours plume passage is estimated to be:

External gamma dose from the plume	0.05 mSv
External gamma dose from deposition	0.3 mSv
Inhalation dose from the plume	1.5 mSv
Total whole body dose	1.85 mSv

The shielding factor obtained by indoor residence is 0.8 for gamma radiation from the plume and 0.25 for gamma radiation from the deposited radioactivity. The reduction factor for inhalation of activity by indoor residence is 0.3.

It is assumed that people under normal circumstances are staying 2 hours outside and 13 hours inside during the period 17.00 to 8.00. The average individual dose accumulated during the plume passage is thus 0.74 mSv for normal living conditions i.e. if no action is taken: (2h × (0.05 + 0.3 + 1.5)mSv + 13h × (0.05 × 0.8 + 0.3 × 0.25 + 1.5 × 0.3)mSV)/15h = 0.74 mSv.

This estimate is very uncertain because only accident and weather forecasts are available at the moment of the decision. The group of experts estimates that the uncertainties in the estimated external gamma doses and the inhalation doses are such that the average individual dose could be 10 times lower with a probability of 0.3 and 10 times higher with a probability of 0.1. The average individual dose range is thus estimated as:

0.074 mSv with a probability of 0.3
0.74 mSv with a probability of 0.6
7.4 mSv with a probability of 0.1

The spread in individual doses for each of these probabilities is assumed to be less than a factor of 10.

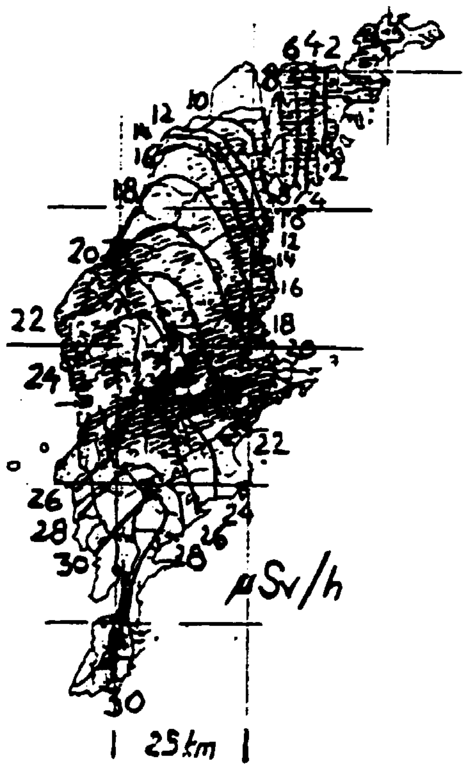
3.2 Deposition Doses in the Secondary Phase

In the morning of June 18th after the plume passage the outdoor dose rate has been measured at different locations at the island and the above mentioned uncertainties in the original estimate has thus disappeared. The result of the survey is shown in Figure 1. In the N E-end of Gotland the measured dose rate is about 1 μSv/h, increasing to about 30 μSv/h in SW-end of the island. In the city of Visby the outdoor dose rate was measured to be 18 - 20 μSv/h.

It is assumed that from the dose rate survey and from census data the group of experts has estimated that **the average individual outdoor gamma dose accumulating over the following 14 days will be 4 mSv.**

The dose distribution, taking into account the living habits on the island without shielding factors, is also estimated by the same group of experts:

Figure 1. Plan of the survey of outdoor dose rates at Gotland on June 18th, morning. Exercise SIEVERT.



The individual dose to 10% of the population is less than or equal to 2 mSv, to 95% of the population the dose is less than or equal 6 mSv and all doses are less than or equal to 10 mSv.

3.3 Deposition Doses in the Late Phase

The average individual doses in the late phase, where the external gamma dose rate is originating from radionuclides of cesium alone, will be **approximately 0.5 mSv/month in the first years after the accident** assuming an average surface contamination density of 1.5 MBq/m^2 of ^{137}Cs).

3.4 Ingestion Doses in the Late Phase

The surface contamination level of ^{137}Cs is assumed to be of the order of 1 - 2 MBq/m^2. The concentration of ^{137}Cs in milk will depend strongly on the season when the accident occurs. Peak concentrations of ^{137}Cs in milk of the order of 2,000 - 8,000 Bq/l in the first year would be possible, with an average concentration over the year following the accident of the order of 400 - 4,000 Bq/l.

The committed collective dose from ingestion of contaminated milk and milk products during the year following the accident would be in the range of 0.006 - 0.05 millimanSv/kg milk.

4 Effects and Costs of Protective Measures

The protective measures considered are:

In the primary phase **sheltering during the plume passage**

In the secondary phase **sheltering** and **evacuation**

In the late phase **relocation, food restrictions** and **decontamination.**

4.1 Sheltering Under the Plume Passage

The countermeasure considered as a possibility in the primary phase is sheltering of the total population in their homes.

On the basis of the information given in section 3.1 it can be calculated that when sheltering the dose to an average individual will be 0.57 mSv ($0.05 \times 0.8 + 0.3 \times 0.25 + 1.5 \times 0.3 = 0.57$ mSv)

The individual dose averted is thus 0.17 mSv ($0.74 - 0.57 = 0.17$ mSv)

As mentioned earlier the uncertainty of this estimate is described by assigning a probability of 0.6 to it and probabilities of 0.3 and 0.1 to values that are a factor of 10 lower or higher respectively.

The probability weighted average individual dose averted is 0.28 mSv.

Sheltering will cause losses to private persons in income and losses to industry and trade. The first hand approximation of monetary costs of sheltering can be estimated on the basis of the per caput Gross National Product (GNP). Direct and indirect monetary costs, for e.g. losses in income i.e. money not earned, losses to industry, trade, traffic, and also damages to property are taken to some extent into account by using the GNP. The per caput GNP in Sweden is 160,000 SEK. It is assumed that one tenth of the GNP during 24 h is gathered during the night, between 17.00 and 8.00 and that 60 % of the population are occupationally active.

Thus the average monetary costs of sheltering is 60 SEK/person (160,000 SEK/(52 week/y $\times$ 5 work days/week $\times$ 10) = 60 SEK/person).

The monetary cost of sheltering those working at night is 1,000 SEK/person (160,000/(0.6 $\times$ 52 $\times$ 5) = 1,000 SEK/person).

The monetary cost of sheltering those not working at night is 0 SEK/person

When the accident becomes known it will arouse concern and public anxiety. The psychological effect of introducing countermeasures may be to enhance or reduce this anxiety.

4.2 Sheltering in the Secondary Phase

One countermeasure considered as a possibility in the secondary phase is sheltering of all pregnant women (500) and all children up to the age of 14 (10,000) in their homes for 14 days. It is assumed that there are two children per family and that the mothers (5,000) will have to stay at home together with their children.

On the basis of the information given in sections 3.1 and 3.2 it can be calculated that *the individual dose averted is 0.25 mSv* (2h + 22h × 0.25) × 4mSv/24h - 4 mSv × 0.25 = 1.25 mSv - 1 mSv = 0.25 mSv).

The dose averted to each sheltered pregnant woman and her unborn child is thus 0.5 millimanSv and the dose averted to each sheltered mother and her two children is 0.75 millimanSv.

For the purpose of this calculation it has been considered that an unborn child corresponds to a born child in order to calculate the total harm. It is assumed that half of the mothers have employment from which they have to be absent.

The average monetary cost of sheltering pregnant women will be 10,000 SEK (160,000 SEK × (2 weeks/52 weeks)/0.6 = 10,000 SEK) assuming that all the pregnant women are occupationally active.

The average monetary cost of sheltering a mother and her two children will be 5,000 SEK (160,000 SEK × (2 weeks/52 weeks)/0.6/2 = 5,000 SEK).

The monetary cost of sheltering a mother who is occupationally active and her two children is 10,000 SEK and 0 SEK for those not occupationally active.

4.3 Evacuation in the Secondary Phase

Another countermeasure considered as a possibility in the secondary phase is evacuation of pregnant women (500) and children up to the age of 14 years (10,000) accompanied by their mothers for 14 days to areas outside Gotland where the dose rate is 10 % of that on Gotland.

For normal indoor residence the individual doses accumulated over the 14 day period following the plume passage are calculated as follows: The average individual dose on the island is (2h + 22h × 0.25) × 4mSv/24h = 1.25 mSv. For an evacuated individual the dose is 0.1 × 1.25 mSv = 0.125 mSv.

The individual dose averted is thus 1.12 mSv (1.25 mSv - 0.125 mSv = 1.12 mSv).

The dose averted to each evacuated pregnant woman and her unborn child is 2.25 millimanSv and the dose averted to each evacuated mother and her two children is 3.38 millimanSv.

The monetary cost of transportation is set to 200 SEK/person and other expenses to 100 SEK per person and day. The loss of GNP is the same as for sheltering on Gotland. The monetary cost of evacuation is thus (14 × 100 + 200) SEK = 1,600 SEK per person plus 10,000 SEK for a pregnant woman and 5,000 SEK for a mother and her two children.

The total average monetary cost of evacuation is thus 11,600 SEK for a pregnant woman and 9,800 SEK for a mother and her two children.

The monetary cost of evacuating an occupationally active mother and her two children is 14,800 SEK and 4,800 SEK for those not occupationally active.

4.4 Relocation in the Late Phase

In the late phase where the external gamma dose rate is originating from radionuclides of cesium alone, the only countermeasure considered is relocation of the total population.

The average individual dose averted by this countermeasure is approximately 0.5 mSv per month in the first years after the accident (assumed average surface density 1.5 MBq/m^2).

The monetary cost of relocation is the sum of the average loss of GNP (if employment is lost as a consequence of the relocation) and the average monthly monetary cost for accommodation and food. As mentioned earlier (Section 4.1) the per caput GNP in Sweden is 160,000 SEK. or 13,300 SEK/month. The monetary cost of food and accommodation could be set at 2,000 Sek/month.

The total monetary cost of relocation for an average individual is thus 15,300 SEK/month. This amount will decrease with time as some are reemployed.

4.5 Food Restrictions in the Late Phase

The only food restriction considered in the late phase is banning of milk. On the basis of the information given in Section 3.4 it can be calculated that *the committed collective dose from ingestion of contaminated milk during the year following the accident will be in the range of 0.006-0.05 millimanSv/kg milk which could be averted* if the contaminated milk produced at Gotland was removed from human consumption.

The monetary cost is assumed to be 7 SEK/kg milk.

4.6 Decontamination in the Late Phase

Experiments with decontamination of urban surfaces and experience from the Chernobyl accident indicate that a realistic large scale reduction factor is of the order of 2. If it is assumed that a large scale decontamination campaign can be carried out, *the individual external dose averted in a lifetime of 70 years will be of the order of 60 mSv per person over this period.*

Cost estimates for decontamination have ranged between 1,000 \$ and 10,000 \$ per person depending on the population density in the area to be decontaminated. 1 US \$ has been set to 7 SEK.

5 Quantitative Decision-Aiding Techniques

5.1 Introduction

In situations where radiation protection is an issue, decision aiding techniques can be used to assist in justifying the action and optimizing the protection by selecting the best option between a number of possible different actions. Two of these techniques will be dealt with here, namely extended cost-benefit analysis and multi-attribute utility analysis. The purpose is to highlight the connexion between the two methods including similarities and differences.

The factors determining the outcome of an analysis are:

1) The specification of the radiological protection factors such as dose averted (benefit) and the monetary cost incurred by intervention, and
2) The criteria to be used in the analysis such as *value functions describing the psychological valuation* of different levels of the radiation protection factors (*attributes*), and *weighting factors* determining the value ratios between them.

It is worth noting that the outcome of an analysis is not influenced by the decision-aiding technique used, as long as the above mentioned factors are not changed.

It is important to recognize that decision aiding techniques are not intended to replace the role and judgement of a decision maker. The objective is to find a balanced action with the assistance of an analysis.

It is a way to help the decision maker to think more clearly about his problem and to bring him further insight and understanding.

Decision making requires trade offs to be made between the harmful and beneficial consequences of every possible solution. Either intuitively or explicitly, the decision maker must identify the attributes relevant to the decision, and value the consequences of the available options against them. The advantage of performing the analysis explicitly, using formal techniques, is that the process is clearly structured and important factors are less likely to be overlooked.

5.2 Cost-Benefit Analysis

The oldest form of decision analysis in radiation protection is the simple cost-benefit analysis where only dose averted and costs are considered. These attributes are described by *linear value functions*, e.g. it is assumed that a certain dose averted has always the same value irrespective of the dose level (inside the stochastic effects range) and a dollar spent has always the same value irrespective of the total amount spent. The ratio between these attributes is fixed by a simple weighting factor, usually called α, a constant monetary value assigned to an averted dose of one manSv.

The optimum option is then simply the one where the difference between the values of the dose averted ($\alpha \times$ dose) and the cost has the largest positive value.

In more complex situations other factors can of course be included in the analysis such as anxiety, reassurance or social disruption caused directly by the countermeasures. This assumes that value functions and weighting factors can be assigned by reasoning, consensus or other suitable methods (*extended cost-benefit analysis*). The value functions have to be independent but they need not be linear and will normally have a curvature of the type described below in Section 5.4.

5.3 Multi-Attribute Utility Analysis

Multi-attribute utility analysis is intended for aiding complex decision making, which involves both quantifiable and less quantifiable factors. The analysis begins with the identification of the set of *options*, or available solutions to the problem. For example in emergency planning, a set of options might be the various intervention levels at which a protective measure should be adopted - including the option not intervening. Options are compared by evaluating their performance with reference to a number of factors, *attributes*, which are relevant to the decision. When deciding upon the optimum intervention level for a protective measure, appropriate attributes might include dose saved, disruption, risk from the protective measure, monetary cost and reassurance provided by the protective measure. Some of these attributes, such as dose saved, are directly quantifiable, whilst others, such as reassurance, are more subjective. In a multi- attribute utility analysis the performances of competing options on an attribute are assessed relative to each other, rather than being converted into a universal measure (eg. currency). Subjective aims are thus more easily encompassed, since relative rather than absolute performances are used.

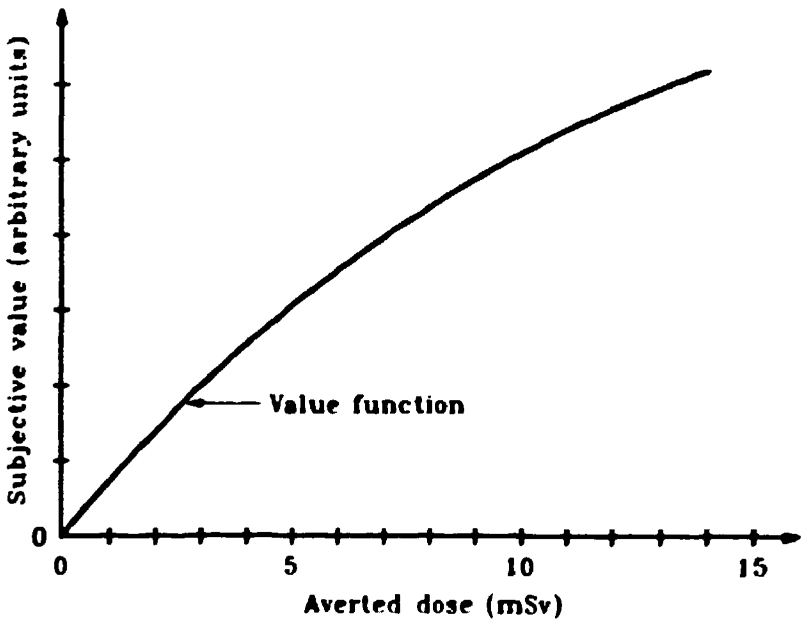
5.4 Value Functions

A value function associates a subjective value to any objective quantity that may be gained or lost.

The value function for gains is normally concave downward so that an extra unit gained adds less to the total subjective gain than the preceding one. It becomes progressively flatter as the gain increases as examplified in Figure 2. This is compatible with the common impression that the difference between a gain of 100 \$ and one of 200 \$ is more outstanding than the difference between a gain of 1,100 \$ and one of 1,200 \$. Such a value function implies a *risk averse attitude, i.e. a certain outcome is preferred to a gamble with an equal or greater mathematical expectation.*

The value function for losses is normally *convex downward* (the objective loss and its subjective value are both negative) so that an extra unit lost adds less to the total subjective loss than the preceding one. This is compatible with the common impression that the difference between a loss of 100 \$ and one of 200 \$ is more outstanding than the difference between a loss of 1,100 \$ and one of 1,200 \$.

Figure 2.



Such a value function implies *a risk seeking attitude*, i.e. a certain outcome is rejected in favour of a gamble with an equal or lower mathematical expectation. If the value function for losses is delineated numerically it resembles the value function for gains although they are not identical.

It is common that *the subjective value of 35 % of an amount to be gained has half the subjective value of that amount.* For example the subjective value of a gain of 35 $ is commonly felt to be half the subjective value of a gain of 100 $ and 350 $ half the value of 1,000 $.

It can be shown mathematically that the value function for an individual who follows this 35 % proportionality is a power function with an exponent of approximately 2/3.

For losses it is common that the subjective (negative) value of an amount to be lost is 40 % of the subjective value of that amount. For example the subjective value of a loss of 40 $ is commonly felt to be half the subjective value of a loss of 100 $ and a loss of 400 $ half the value of 1,000 $. The corresponding power function has an exponent of approximately 3/4.

The power function model breaks down when the gains or losses increase out of proportion to the individual's normal economic capacity. For extremely large gains, the value function becomes almost flat as the individual becomes indifferent to the choice between enormous gains. For losses, the value function becomes very steep (changes from risk search to risk averseness) when possible losses become so large that they would ruin the individual.

Individuals differ naturally in their attitudes towards risks and towards money and the value functions presented here are only a summary of the attitudes of the majority of people, not a scientific law.

Radiation protection measures affecting the general population have, at the end of the day, to be paid for by this population, and the optimum solution is thus dependent on the population's willingness to pay for protection or expressed in another way: Dependent on the value functions corresponding to the preferences of that population.

5.5 Utility Functions

While, in extended cost-benefit analysis value functions are used directly and weighting factors between radiation protection factors (or attributes) are ratios between units of the various attributes, this is different in multi-attribute utility decision analysis. In multi-attribute utility analysis, scores (or utilities) are assessed in terms of how valued, or desirable, each attribute value is to the decision maker in order that options may be compared. Utility is measured on a scale from 0 (worst performance) to 1 (best performance).

For some attributes such as averted dose (a desirable attribute), a high score (utility or subjective value) implies a high attribute value. For others such as monetary cost (an undesirable attribute), it is the lowest score which implies the highest attribute value. The relationship between a score and its attribute value is not always linear, since the subjective value (score or partial utility) associated with a unit on the attribute scale may change according to the location upon the scale at which the unit lies. Variation in preference along a particular scale, or *partial utility functions*, are dependent of the individual or group in question and of the circumstances.

In utility analysis the value function of an attribute is transformed to a partial utility function. As an example Figure 3 shows the connection between a partial utility function and the corresponding value function for averted dose (a desirable attribute) with the averted dose on the abscissa and the subjective value (subjective benefit, partial utility or score) in arbitrary units on the ordinate. If the lowest averted dose resulting from any of the options of intervention is 5 mSv and the highest averted dose that result from any of the options is 10 mSv, then 5 mSv is assigned a utility of 0 and 10 mSv a utility of 1 and the »range« is (10 - 5) = 5 mSv - as shown on the bold drawn part of Figure 3. This figure shows the close connection between ordinary value functions and partial utility functions. The partial utility function for desirable attributes coincides with the value function between the abscissae 5 and 10 (the »range«).

The partial utility part of the figure is redrawn in Figure 4a. If the abcissa had not been a desirable attribute (averted dose) as in Figure 4a but an undesirable one, e.g. received dose, then the option giving the highest received dose would be assigned a partial utility of 0 and the lowest received dose a partial utility of 1. The partial utility function would have had an appearance as shown in Figure 4b (a mirror image of the value function around a horizontal line).

For gains or desirable attributes (Figure 4a) the utility function is concave downward. This

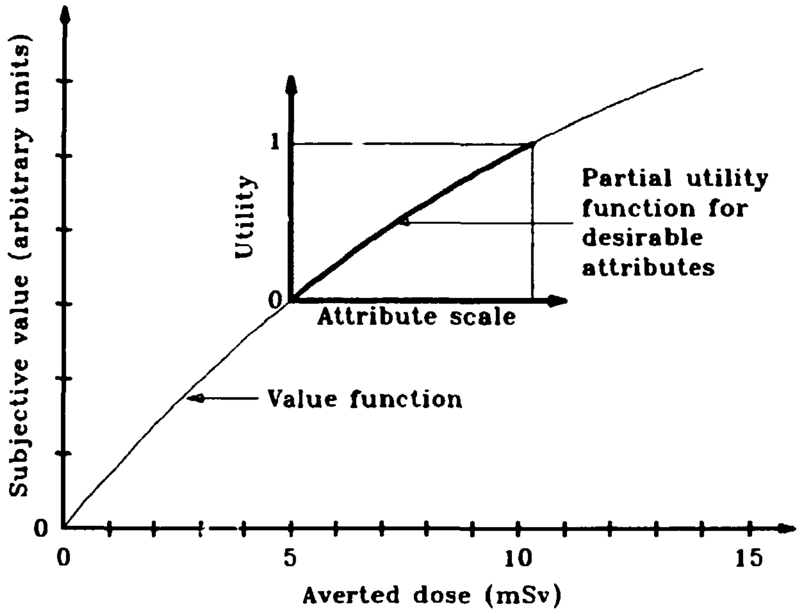


Figure 3.

Figure 4a.

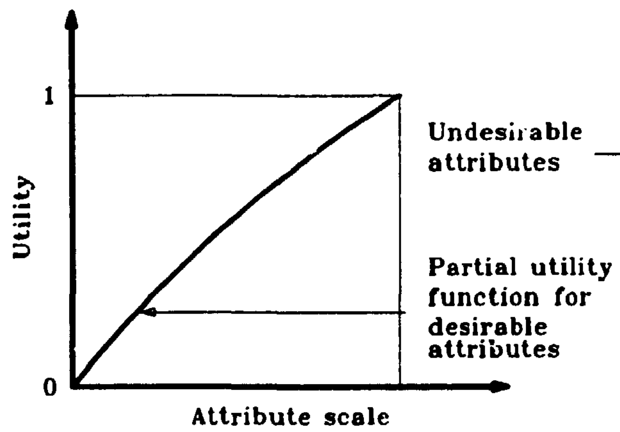
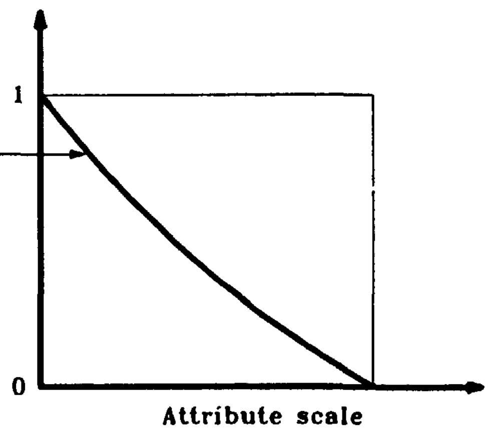


Figure 4b.



signifies a risk averse attitude. For loses or undesirable attributes (Figure 4b) the utility function is concave upward. This signifies a risk seeking attitude.

The utility functions can be assessed e.g. by asking the decision maker for his midpoint preference between the lowest and highest attribute abscissae. This could e.g. be at 40 % of the difference. The corresponding utility would be 0.5 giving one point on the utility curve. More points can be assessed by asking the decision maker for his midpoint preferences between the abscissae 0 and 40 % and between 40 % and 100 % and so on.

5.6 Weighting Factors in Utility Analysis

The overall performance of each option is measured in terms of *total utility,* achieved by weighing and summing the values associated with each attribute. *Weights* reflect not only the intrinsic importance of the attribute to the decision maker (eg. health effects may be regarded as inherently more important than monetary costs) but also the length of the scale upon which it has been measured. Thus if there is little difference between the attribute values resulting from the available options, then the scale is short, whereas if there are considerable differences then the scale is long and the weight assigned correspondingly higher.

In utility analysis the *weighting factors* (or scaling constants) are proportional to the the value difference over the ranges of attributes (the value corresponding to a utility of 1 minus the value corresponding to a utility of 0). If e.g. w_x is the weighting factor for cost and w_s the weighting factor for dose then:

w_x /(value of difference in cost between utilities 0 and 1) =
w_s /(alpha × value of difference in dose between utilities 1 and 0).

Usually the weighting factors are normalized so that $\Sigma w_i = 1$.

The weighting factors can be determined e.g. by *so-called swing weighting:*

For two particular options A and B, the decision maker is asked to imagine that all the attributes, except attribute x and attribute y, have the same partial utility for the two options.

He is further asked to imagine that attribute x has a partial utility of 1 and attribute y a partial utility of 0 for option A, and that for option B it is vice versa.

If he now prefers option A for option B then to him obviously $w_x > w_y$. Suppose now that for option B, the size of attribute x is lowered so much that the the decision maker is indifferent between the two options and that this size is 0.6x. Then $w_y/w_x = 0.6$.

If the process is repeated for other pairs of options, a complete set of weighting factors can be derived.

5.7 Total Utility of Options

For each option, the partial utilities corresponding to the abscissae of all the attributes are determined by the corresponding utility functions. These partial utilities are each multiplied by the appropriate weighting factor. The sum of these products is called *the total utilities of the options.*

The numerical values of the total utilities provides a ranking order of the options. The option with the highest utility is the optimal one according to the decision makers preferences.

This procedure presupposes that the partial utility functions are all independent.

When the partial utility functions and the weighting factors are fixed, it is easy to derive the value functions and the unit weighting factors that could be used in an extended cost-benefit analysis. This can lead to the optimal option without the use of total utilities but with the same result with respect to ranking.

The difference would of course be, that in extended cost-benefit analysis an attempt would be made to replace the preferences of the decision maker by more common »objective« criteria. Perhaps these would be e.g. value functions of the power function type with exponents of 2/3 and 3/4 for gains and losses, respectively, which are typical for the majority of the general population.

5.8 References

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6 Optimization of Protective Measures

6.1 Cost-Benefit Analysis

A Summary of Annex I

International guidance on intervention comprise the principles of justification/optimization as basis for intervention in de facto situations, ie. situations where the radiation source already is present in the environment.

Intervention is **justified** when the introduction of protective measures will achieve more good than harm. The level at which the intervention is introduced, and the level at which it is later withdrawn, should be **optimised** so the intervention will produce the **maximum benefit**, ie. do the most good.

For a protective measure which is spread over time like sheltering, evacuation and relocation, the intervention level of dose (and the corresponding derived intervention level) for **optimum protection** is determined by the cost of the protective measure per unit time, a, and the monetary value of the unit collective dose, α. The optimum protection would be obtained if the protective measure is introduced at a level where the effective individual dose per unit time exceeds the value, $\dot{E}_{opt}$, and is terminated when the effective dose per unit time drops below this value. The Intervention Level (IL), $\dot{E}_{opt}$, will be:

$$IL = \dot{E}_{opt} = \frac{a}{\alpha} \tag{1}$$

For contaminated foodstuffs, the Intervention Level expressed as activity concentration in the foodstuff, C, can be calculated from the cost per unit mass of the foodstuff, b, and the monetary value of the unit collective dose, α, as:

$$IL = C_{opt} = \frac{b}{\alpha \cdot e} \tag{2}$$

where e is the committed dose per unit activity ingested.

In the optimization calculations three different values of α have been used:

1,000 \$/manSv, 20,000 \$/manSv and 100,000 \$/manSv.

The upper value has been included because the Nordic radiation protection Authorities have advocated that »up to 100,000 \$ would be a reasonable value to spend for reducing the collective dose by 1 manSv«.

Sheltering in the Primary Phase

The averted individual doses by sheltering in the primary phase are 0.17 mSv/15 h. The optimized ILs for sheltering in the primary phase have been calculated to be in the range of **0.1 - 150 mSv/15 h,** depending on the sheltering scenario and the monetary value of α. Sheltering of the total population is therefore justified only for the upper value of α for which the averted dose of 0.17 mSv/15 h > IL.

Sheltering in the Secondary Phase

The averted individual doses by sheltering in the secondary phase are 0.25 mSv/14 d. The optimized ILs for sheltering in the secondary phase (14 days) have been calculated to be in the range of **7 - 1,500 mSv/14 d,** depending on the sheltering scenario and the monetary value of α. Sheltering is therefore not justified for any of the considered α-values because the averted dose of 0.25 mSv/14 d < IL.

Evacuation in the Secondary Phase

The averted individual doses by evacuation in the secondary phase are 1.12 mSv/14 d. The optimized ILs for evacuation in the secondary phase have been calculated to be in the range of **7 - 2,000 mSv/14 d,** depending on the evacuation scenario and the monetary value of α. Evacuation is therefore not justified for any of the considered α-values because the averted dose of 1.12 mSv/14 d < IL.

Relocation in the Long-Term Phase

The averted individual doses by relocation in the long-term phase are 0.5 mSv/month. The optimized ILs for relocation (and resettlement) in the long-term phase have been calculated for the three α-values to be in the range of **3 - 2,000 mSv/month,** depending on the relocation scenario and the monetary value of α.

Relocation is therefore not justified for any of the considered α-values because the averted dose of 0.5 mSv/month < IL.

Milk Restrictions

The averted collective committed dose by milk restrictions the first year after theaccident is assumed to be 0.02 millimanSv/kg milk, corresponding to an activity concentration of ^{137}Cs of 1,600 Bq/kg. The optimized ILs for the introduction (and withdrawal) of protective measures in form of removing the milk from human consumption have been calculated to be in the range of **800 - 80,000 Bq/kg,** depending on the monetary value of α.
Milk restriction is therefore justified only for the upper value of α for which the cesium concentration in milk of 1,600 Bq/kg > IL.

In summary, the individual doses that could be averted are of a magnitude that in most cases would not justify protective measures. Furthermore, the averted doses are below or close to the lower level of the intervention level range given in the indicative guidance from the IAEA. According to the IAEA, it would be erroneous to select arbitrarily values from the bottom of the ranges given in the guidelines. Given the disruptive character of the protective measures of sheltering, evacuation and relocation, the optimum level for intervention for these measures would probably fall outside the IAEA ranges at the top level.

6.2 Multi-Attribute Utility Analysis

A Summary of Annex II

The basic principles of radiation protection are based on the justification and optimization of protective actions. The decision analysis, although closely entwined with these principles, does not interpret the results with this terminology. The aim of decision analysis is to find the best solution to a problem based on the rationality of the decision maker(s). However, the result of decision analysis can be translated to correspond to the basic principles of radiation protection.

At the beginning of a decision analysis all feasible protective actions are defined, including the action of doing nothing - the acceptance of status quo. It is the existing situation which forms the basis to which protective actions are compared when they are assessed as justified or not - with respect to the preferences of society represented by a decision maker. The preferences and trade-offs - the judgemental inputs to analysis - form the basis for justification. A protective action is justified if the values connected to it are grater than those of no-action.

The optimization of the intervention is achieved by ranking all feasible actions defined, for example, by various intervention levels. The action with the highest ranking will produce the maximum benefit. In optimization it is thus assumed that all actions and attributes are defined at the beginning of an analysis. In practice, however, it is not possible to define all actions before making some preliminary numerical assessments and running through some rough calculation to gain a feeling for what numbers are important and require refined assessment. The optimization of intervention means this iterative process of maximization of protection in all its essentials. The setting of an intervention level in an accident situation or in planning of the intervention levels is seldom a purely mathematical problem.

The contamination level will affect the relative importance of factors and preferences of a decision maker. The assessment of intervention levels with a scenario and a contamination level close to trigger the implementation of protective action helps to avoid biases and amplifies the feeling of which factors that are important.

All important attributes and feasible actions should be included in the analysis. Well defined attributes facilitate the process of ensuring that the final set of attributes actually captures all the relevant and useful values. In applications of decision analysis Winterfeldt and Edwards (Wi86) have often found themselves suggesting to decision makers, for example, that the political branches of a decision should be considered in evaluating its consequences. In their experience, 'decision makers too often ignore this slippery issue and are bitten by it after the decision is made'. Also they encourage decision makers to be open and explicit about selfish values and motives. 'In almost all applications decision makers benefited from clarification of all their values'.

The most important factor affecting the decision of a protective action in analyses performed is the trade-off value (the α-value) between a dose averted and the monetary costs of an action. The large range of the intervention level is due to the range of the trade-off value. An increase in understanding of how to assess the trade-offs between all attributes will reduce the range of intervention levels and will make other factors, e.g. the shape of a utility function, more important in a decision.

The Primary Phase

In the primary phase the intervention level is 3.7 mSv for sheltering the whole population given as the outside dose meter reading accumulated during 15 hours. Calculations are based on the central trade-off value of 140 000 SEK/manSv. The range of the intervention level corresponding to the range of the α-value - of 7,000 - 700,000 SEK/manSv is 0.2 - 20 mSv. Sheltering is justified at the dose level of 1.85 mSv if the α-value is higher than 280 000 SEK/manSv.

The Secondary Phase

In the secondary phase sheltering or evacuation is not justified within the given range of the trade-off value. The intervention level for evacuation is 80 mSv using the central α-value of 140 SEK/mSv. The range of the intervention level is 4 - 400 mSv, corresponding to the range of the α-value between dose and cost.

Milk Restrictions

Withdrawing the milk from consumption is justified within the given range of the α-value. The intervention level, given as the mean concentration of ^{137}Cs, is 350 Bq/l during the first year after the accident. The intervention level is 200 Bq/l in the first month after the accident given as the mean concentration of ^{137}Cs during the first month. The range of the intervention level corresponding to the range of α-value is 20 - 2000 Bq/l in the first year, and 10 - 1000 Bq/l in the first month.

7 Conclusion

The main purpose of this study has been to demonstrate the setting of intervention levels to be used in nuclear accident situations. As background for selecting appropriate types of countermeasures the scenario »Exercise Sievert« has been chosen as a case study.

In order to obtain the necessary background for the formulation of an intervention strategy not only the total population as such should be considered, but the total population should be split into smaller subgroups well defined with regards to a.o. radiation sensitivity and costs. In this analysis the society was split into the groups mentioned below, mainly caused by the differing costs of the countermeasures as applied in the different population groups. The grouping considered is described in Section 4.

Two disparate analysis methods have been used: **cost-benefit analysis and multi-attribute utility analysis.**

7.1 Cost-Benefit Analysis

The cost-benefit analysis has then shown, that it is justified and optimized to avert the following doses for an α-value of 20,000 $/manSv:

An individual averted dose of:

0.4 mSv/15 h	for sheltering the total population in the primary phase
7 mSv/15 h	for sheltering those working at night
70 mSv/14 d	for sheltering pregnant women
40 mSv/14 d	for sheltering mothers + children
70 mSv/14 d	for sheltering mothers working at night + children
80 mSv/14 d	for evacuating pregnant women
70 mSv/14 d	for evacuating all mothers + children
100 mSv/14 d	for evacuating mothers occupationally active + children
30 mSv/14 d	for evacuating mothers not occupationally active + children
100 mSv/month	for relocating the total population in the late phase

and a collective averted dose of:

0.02 millimanSv/kg	for banning milk (in the case of ^{137}Cs this corresponds to a concentration of 4 kBq/kg except for pregnant women where the corresponding concentration is 2 kBq/kg).

In the detailed cost-benefit calculations in Annex I three α-values are used. The central α-value is 20,000 US $/manSv, while the upper and lower values, used to test the sensivity of the calculations, are α-values 20 times lower and 5 times higher respectively.

The table in the Annex I, summarizing the results of the justification/optimization calculations for the different protective measures is repeated here:

Intervention Levels for Exercise Sievert Gotland

Sheltering primary phase	Averted dose	IL	Justification
Total population	0.17 mSv/15 h	10 mSv/15 h	not justified
		0.4 mSv/15 h	not justified
		0.1 mSv/15 h	justified
Those working at night	0.17 mSv/15 h	150 mSv/15 h	not justified
		7 mSv/15 h	not justified
		1 mSv/15 h	not justified
Sheltering secondary phase	**Averted dose**	**IL**	**Justification**
Pregnant women	0.25 mSv/14 d	1,500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
All mothers and their children	3 x 0.25 mSv/14 d	700 mSv/14 d	not justified
		40 mSv/14 d	not justified
		7 mSv/14 d	not justified
Mothers working at night and their children	3 x 0.25 mSv/14 d	1,500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
Evacuation secondary phase	**Averted dose**	**IL**	**Justification**
Pregnant women	1.12 mSv/14 d	1,500 mSv/14 d	not justified
		80 mSv/14 d	not justified
		20 mSv/14 d	not justified
All mothers and their children	3 x 1.12 mSv/14 d	1,500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
Occupationally active mothers and their children	3 x 1.12 mSv/14 d	2,000 mSv/14 d	not justified
		100 mSv/14 d	not justified
		20 mSv/14 d	not justified
Non-occupationally active mothers and their children	3 x 1.12 mSv/14 d	700 mSv/14 d	not justified
		30 mSv/14 d	not justified
		7 mSv/14 d	not justified
Relocation late phase	**Averted dose**	**IL**	**Justification**
With loss of job	0.5 mSv/month	2,000 mSv/month	not justified
		100 mSv/month	not justified
		20 mSv/month	not justified
Without loss of job	0.5 mSv/month	300 mSv/month	not justified
		10 mSv/month	not justified
		3 mSv/month	not justified
Milk restrictions late phase	**Averted dose**	**IL**	**Justification**
Total population	0.02 manmSv/kg	80 kBq/kg	not justified
		4 kBq/kg	not justified
		0.8 kBq/kg	justified

It is noted that the IL-values depend on the chosen α-value and the local cost level only - **but not on the accident scenario.**

Applying these α-values to the scenario at hand gives the result that:

Intervention is not justified except for the highest α-value (100,000 US $/manSv) and then only for:

Sheltering in the primary phase and milk banning.

7.2 Multi-Attribute Utility Analysis

Applying multi-attribute utility analysis to the scenario yields the same results with respect to the choice of countermeasures and their justification as the cost-benefit analysis.

This is a general rule that applies as long as the same value functions (or utility functions and weighting factors) are used.

For the sake of completeness it should be mentioned, that different costs for one kg of milk have been used in the two methods: 7 SEK/kg in the cost-benefit analysis and 3 SEK/kg (production cost) in the multi-attribute utility analysis.

The essential aim of a decision analysis is to help the decision maker to think more clearly about the problems and to bring him further insight and understanding. In the light of that understanding the decision maker must make his choice.

In group decisions - in social choices - at least in a democracy, the decision maker(s) represents the population - on behalf of which the decision is made - and its preferences, which are expected to be considered in a fair and just process.

One of the aims of decision analysis is to structure the problem such that important aspects are not overlooked. This is often done by arranging a so-called *decision conference*, where all aspects of the problem are discussed freely and informally. Such a decision conference has not been arranged in connection with the present study.

In the present analysis only tangible attributes such as averted radiation doses and the monetary costs of countermeasures have had an influence on the result. Where more intangible factors of a psychological or political character are significant, the resulting recommended countermeasures - with and without these factors taken into account - should be made public in order to ensure transparency to the population.

How to tackle such factors is indicated in Appendix II.

ANNEX I. Cost Benefit Analysis

by

Per Hedemann Jensen

1 Introduction

A case study of intervention level setting following a hypothetical accident at the nuclear power plant Ignalina in Lithuania with a release of fission products to the atmosphere has been made. Due to easterly winds, the plume will pass the island of Gotland for around 15 hours, and heavy showers will cause ground contamination of fission products by wet deposition. The purpose of the study is to demonstrate for Nordic conditions the use of the intervention principles found in international guidance [1,2]. These can be summarised as the principles of **justification, optimization and below deterministic effects.**

Intervention Levels (ILs) which are based on radiation risk reduction and monetary costs form the basis for the inputs to the decision making process from the radiation protection community. The input from the radiation protection community to the decision making process should be published **separately** to ensure transparency to the public. Other factors than those of strictly radiological protection nature will, however, enter the decision making process. These other factors will often have greater weight than the radiological protection factors but they are the sole responsibility of the decision maker and should **not** emerge from the radiation protection community.

2 Protective Measures and Doses Averted

2.1 Sheltering in the Primary Phase

If the people are sheltered in their homes during the plume passage, the external and the internal doses will be reduced because of the protective effect of the buildings. The reduction of the average individual dose by sheltering, ie. the average individual dose **averted**, has been calculated to be:

Averted individual dose: 0.17 mSv/15 h

The monetary cost has been estimated to be 60 SEK in average per person summing up to 2.8 Million SEK for the whole population. The average cost of sheltering only those working at night has been estimated to be 1,000 SEK per person.

2.2 Sheltering in the Secondary Phase

In the secondary phase of 14 days, three different scenarios of sheltering have been considered. Firstly, all pregnant women are sheltered in their homes for 14 days. Secondly, all mothers and children are sheltered. Thirdly, only those mothers working at night and their children are sheltered.

2.2.1. Sheltering of Pregnant Women

The average individual dose **averted** by sheltering for a period of 14 days has been calculated to be:

Averted individual dose: 0.25 mSv/14 d

The average monetary costs of sheltering 500 pregnant women have been estimated to 10,000 SEK/person summing up to be 5 Million SEK, assuming that all pregnant women are occupationally active.

2.2.2. Sheltering of all Mothers and Children

The average individual dose averted by sheltering all mothers and their two children below the age of 14 years (15,000 persons) has been calculated to be:

Averted individual dose: 3 x 0.25 mSv/14 d

The monetary costs have been estimated to be 5,000 SEK per mother plus children, assuming that half of the mothers have normal work from which they have to be absent. The total cost will thus be 25 Million SEK.

2.2.3. Sheltering of Mothers Working at Night and Their Children

The average individual dose averted by sheltering mothers working at night and their two children has been calculated to be:

Averted individual dose: 3 x 0.25 mSv/14 d

The monetary costs of sheltering mothers who are working at night have been estimated to be 1,000 SEK/person.

2.3 Evacuation in the Secondary Phase

Four different evacuation scenarios have been considered. Firstly, all pregnant women are evacuated for a period of 14 days to areas where the dose rate is 10% of the dose rate at Gotland. Secondly, all mothers and their children below the age of 14 years are evacuated. Thirdly, only those mothers occupationally active and their children are evacuated. Fourthly, only mothers not occupationally active and their children are evacuated.

The average individual dose **averted** by evacuation for 14 days has been calculated to be:

Averted individual dose: 1.12 mSv/14 d

The average monetary costs of evacuation have been estimated to be 11,600 SEK/person for pregnant women, 9,800 SEK/mother+2 children, 14,800 SEK/mother+2 children for occupationally active mothers, and 4,800 SEK/mother+2 children for non-occupationally active mothers.

2.4 Relocation in the Long-Term Phase

The average individual doses **averted** by relocation in the long-term phase, where the external γ-dose rate is originating alone from radionuclides of cesium, will be approximately 0.5 mSv/month in the first years after the accident (assumed surface contamination density with ^{137}Cs of 1.5 MBq/m^2).

The monetary costs of relocation have two major components: the average loss of income (if employment is lost as a consequence of the relocation) and the average monthly cost for accomodation and other costs such as deterioration of property etc. The monthly cost of food and accomodation and other costs could cautiously be set to 2.000 SEK/month/person [3]. If the job is lost as a result of the relocation the average cost has been taken to be 1/12 of the GNP per capita, corresponding to 13.300 SEK/month. This cost will decrease with time when people are reemployed.

2.5 Milk Restrictions

The surface contamination level of ^{137}Cs is assumed to be of the order of 1 - 2 MBq/m^2. The concentration of ^{137}Cs in milk will depend strongly on the time of year when the accident occurs. Peak concentrations in milk of ^{137}Cs of the order of 2.000 - 8.000 Bq$\cdot\ell^{-1}$ in the first year would be possible, with an average concentration over the the year following the accident of the order of 400 - 4,000 Bq$\cdot\ell^{-1}$.

The committed collective dose from ingestion of contaminated milk and milk products during the year following the accident would be in the range of 0.006-0.05 manmSv/kg milk which could be averted, if the contaminated milk produced at Gotland was removed from human consumption. The cost is assumed to be 7 SEK/kg milk/milk product [3].

3 Justification and Optimization of Protective Measures

There has been much confusion over the role of dose limits in the establishment of intervention following an accident. Several factors have contributed to this confusion, not least the numerically equality between some of the intervention levels of dose proposed and the annual dose limits. The aims of intervention levels are quite different from those of dose limits. The dose limits recommended by the ICRP are set for controlling **increases** of radiation exposure for practices. Intervention levels relate specifically to protective measures to **decrease** existing radiation exposure.

The dose **averted** by the protective measures is the relevant quantity for judging the radiological benefits of these measures and this quantity should be used as the basis for expressing quantitative intervention criteria.

3.1 Application of Basic Justification/Optimization Principles

International guidance on intervention [1,2] comprise the principles of justification and optimization as basis for intervention in de facto situations, ie. situations where the radiation source already is present in the environment.

Intervention is **justified** when the introduction of protective measures will achieve more good than harm. The level at which the intervention is introduced, and the level at which it is later withdrawn, should be optimised so the intervention will produce the maximum benefit, ie. do the most good. Although these two principles of **justification** and **optimization** are stated separately, it is necessary to consider them together when reaching a decision on intervention.

The general case is likely to be that there is a range of protective measures that would give more good than harm, so that intervention is justified for all these measures, with the selection of the most appropriate one depending on the particular circumstances.

In addition, all possible effort should be made to prevent deterministic health effects. For the accident scenario under consideration such effects are not possible at the given dose levels including radiation induced malfunctions of the embryo which have a **threshold** of about **0.1 Gy** [2].

The net benefit, B, achieved by a protective measure can be expressed as:

$$B = \Delta Y - X \tag{1}$$

where

ΔY is the cost equivalent of the averted collective dose ΔS

X is the monetary cost of implementing the protective measure

The cost equivalent of the averted dose is calculated from the monetary value assigned to the unit collective dose, α:

$$\Delta Y = \alpha \cdot \Delta S \tag{2}$$

The maximum net benefit can be found by an optimization process which can be conceptualized in simple differential cost-benefit terms:

$$\frac{dB(I)}{dI} = \frac{d\Delta Y(I)}{dI} + \frac{dX(I)}{dI} = 0 \tag{3}$$

where I is the intervention level. At the optimum point, i.e. where the net benefit B is maximum (and positive), the intervention level I, expressed in terms of averted dose, would under the given circumstances correspond to an action level above which the protective measure should be introduced and below which it should not.

For a protective measure which is spread over time like sheltering, evacuation and relocation, the intervention level of dose per unit time (and the corresponding derived intervention level) for **optimum protection** is determined by the cost of the protective measure per unit time, a, and the monetary value of the unit collective dose, α [3]. The optimum protection would be obtained if the protective measure is introduced when the effective individual dose per unit time exceeds a given value, $\dot{E}_{opt}$, and is terminated when the effective dose per unit time drops below this value. The derived intervention level, $\dot{E}_{opt}$, will be:

$$\dot{E}_{opt} = \frac{a}{\alpha} \tag{4}$$

Based on the newly modified risk factor recommended by the ICRP [2], an **upper level** of α can be set at **20,000 \$/manSv** [3], equivalent to approximately 140,000

SEK/manSv, assuming that the monetary value of one year of lost life due to radiation induced cancer should not exceed, in average for the society, the Gross National Product (GNP) per capita (~ 27.000 \$/year in 1990). However, the Nordic Radiation Protection Authorities have advocated that "up to 100.000 \$ would be a reasonable value to spend for reducing the collective dose by 1 manSv". The optimization calculations include - for illustrative purposes only - this "high" α-value and also a "low" α-value of 1.000 \$/manSv.

3.1.1. Sheltering in the Primary Phase

The averted collective dose in the primary phase by sheltering the total population during the plume passage is 9.5 manSv and the total cost is 3.4 Million SEK. The net benefit, B, can therefore be calculated from (1) and (2) to be:

$$B_1 = 7.000 \text{ SEK/manSv} \cdot 9.5 \text{ manSv} - 3.4 \text{ MSEK}$$
$$= -3.33 \text{ MSEK}$$

$$B_2 = 140{,}000 \text{ SEK/manSv} \cdot 9.5 \text{ manSv} - 3.4 \text{ MSEK}$$
$$= -2.07 \text{ MSEK}$$

$$B_3 = 700.000 \text{ SEK/manSv} \cdot 9.5 \text{ manSv} - 3.4 \text{ MSEK}$$
$$= 3.25 \text{ MSEK}$$

When the net benefit is negative, sheltering is not justified based on radiological protection factors of risk reduction and monetary costs alone. Sheltering is justified only if the monetary value assigned to the unit collective dose is higher than 300.000 SEK as in case 3 with the "high" α-value.

The cost of sheltering for 15 hours has been determined to be 60 SEK/person if all people are sheltered. The IL for the introduction of sheltering for 15 hours can then be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{60 \text{ SEK/15 h}}{7{,}000 \text{ SEK/Sv}} \cong 10 \text{ mSv/15 h}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{60 \text{ SEK/15 h}}{140{,}000 \text{ SEK/Sv}} \cong 0.4 \text{ mSv/15 h}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{60 \text{ SEK/15 h}}{700{,}000 \text{ SEK/Sv}} \cong 0.1 \text{ mSv/15 h}$$

The cost of sheltering those working at night has been has been determined to be 1,000 SEK/person. The IL for the introduction of sheltering can therefore be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{1{,}000 \text{ SEK/15 h}}{7{,}000 \text{ SEK/Sv}} \cong 150 \text{ mSv/15 h}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{1{,}000 \text{ SEK/15 h}}{140{,}000 \text{ SEK/Sv}} \cong 7 \text{ mSv/15 h}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{1.000 \text{ SEK}/15 \text{ h}}{700.000 \text{ SEK/Sv}} \cong 1 \text{ mSv}/15 \text{ h}$$

The meaning of $\dot{E}_{opt}$ is that only if the individual doses averted by sheltering during the 15 hours plume passage would exceed $\dot{E}_{opt}$, the measure should be introduced. As the averted individual dose by sheltering is 0.17 mSv/15 h (see Sect. 2.1), only in case 3 for the total population, for which $\dot{E}_{opt}$ < 0.17 mSv, sheltering is justified as also determined from the net benefit, $B_3 > 0$.

Sheltering of those working at night is not justified for any of the considered α-values. Sheltering of those not working at night is, however, justified under all circumstances because the cost is approximately zero.

3.1.2. Sheltering in the Secondary Phase

Pregnant women

The averted collective dose in the secondary phase by sheltering all pregnant for 14 days is 0.25 manSv and the total cost is 5 Million SEK. The net benefit, B, will be:

$$B_1 = 7.000 \text{ SEK/manSv} \cdot 0.25 \text{ manSv} - 5 \text{ MSEK} = -4.99 \text{ MSEK}$$

$$B_2 = 140{,}000 \text{ SEK/manSv} \cdot 0.25 \text{ manSv} - 5\text{MSEK} = -4.97 \text{ MSEK}$$

$$B_3 = 700.000 \text{ SEK/manSv} \cdot 0.25 \text{ manSv} - 5 \text{ MSEK} = -4.83 \text{ MSEK}$$

Sheltering of pregnant women is **not** justified based on radiological protection factors of risk reduction and monetary costs alone but is justified only if the monetary value assigned to the unit collective dose is higher than 20 Million SEK.

The average cost of sheltering all pregnant women for 14 days have been estimated to be around 10.000 SEK/person. The IL for the introduction of sheltering for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{10.000 \text{ SEK}/14 \text{ d}}{7.000 \text{ SEK/Sv}} \cong 1.500 \text{ mSv}/14 \text{ d}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{10{,}000 \text{ SEK}/14 \text{ d}}{140{,}000 \text{ SEK/Sv}} \cong 70 \text{ mSv}/14 \text{ d}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{10.000 \text{ SEK}/14 \text{ d}}{700.000 \text{ SEK/Sv}} \cong 10 \text{ mSv}/14 \text{ d}$$

The averted individual dose by sheltering pregnant women and children is 0.25 mSv/14 d (see Sect. 2.2.1), which is far below $\dot{E}_{opt}$ even for the highest α-value. Therefore, sheltering of pregnant women in the secondary phase is not justified for any of the considered α-values.

All mothers and their children

The averted collective dose by sheltering all mothers and their two children for 14 days is 3.75 manSv and the total cost is 25 Million SEK. The net benefit, B, will be:

$$B_1 = 7.000 \text{ SEK/manSv} \cdot 3.75 \text{ manSv} - 25 \text{ MSEK}$$
$$= -24.97 \text{ MSEK}$$

$$B_2 = 140{,}000 \text{ SEK/manSv} \cdot 3.75 \text{ manSv} - 25\text{MSEK}$$
$$= -24.48 \text{ MSEK}$$

$$B_3 = 700.000 \text{ SEK/manSv} \cdot 3.75 \text{ manSv} - 25 \text{ MSEK}$$
$$= -22.38 \text{ MSEK}$$

Sheltering of mothers is not justified based on radiological protection factors of risk reduction and monetary costs alone, but is justified only if the monetary value assigned to the unit collective dose is higher than 7 Million SEK.

The average cost of sheltering all mothers and their two children for 14 days have been estimated to be around 5.000 SEK/mother + 2 children. The IL for the introduction of sheltering for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{5.000 \text{ SEK/14 d}}{7.000 \text{ SEK/Sv}} \cong 700 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{5{,}000 \text{ SEK/14 d}}{140{,}000 \text{ SEK/Sv}} \cong 40 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{5.000 \text{ SEK/14 d}}{700.000 \text{ SEK/Sv}} \cong 7 \text{ mSv/14 d}$$

The averted individual doses (per mother + 2 children) are far below $\dot{E}_{opt}$ even for the highest α-value. Therefore, sheltering of mothers and their children is not justified for any of the considered α-values.

Mothers working at night and their children

The average cost of sheltering mothers working at night and their two children has been estimated to be around 10.000 SEK/mother + 2 children. The IL for the introduction of sheltering for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{10{,}000 \text{ SEK/14 d}}{7{,}000 \text{ SEK/Sv}} \cong 1{,}500 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{10{,}000 \text{ SEK/14 d}}{140{,}000 \text{ SEK/Sv}} \cong 70 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{10.000 \text{ SEK/14 d}}{700{,}000 \text{ SEK/Sv}} \cong 10 \text{ mSv/14 d}$$

The averted individual doses (per mother + 2 children) are far below $\dot{E}_{opt}$ even for the highest α-value. Sheltering of mothers working at night is therefore not justified for any of the considered α-values.

It should be emphasized that long-term sheltering, that is for more than about 12 hours, may cause social, medical and hygiene problems, except in specially designed facilities. For a period of 24 hours or longer, food and medical care for shelter occupants will also need to be considered [5].

3.1.3. Evacuation in the Secondary Phase

Pregnant women

The averted collective dose in the secondary phase by evacuating pregnant women is 1.13 manSv and the total cost is 5.8 Million SEK. The net benefit, B, will be:

$$\begin{aligned} B_1 &= 7{,}000 \text{ SEK/manSv} \cdot 1.13 \text{ manSv} - 5.8 \text{ MSEK} \\ &= -5.79 \text{ MSEK} \end{aligned}$$

$$\begin{aligned} \mathbf{B_2} &= \mathbf{140{,}000 \text{ SEK/manSv} \cdot 1.13 \text{ manSv} - 5.8 \text{ MSEK}} \\ &= \mathbf{-5.64 \text{ MSEK}} \end{aligned}$$

$$\begin{aligned} B_3 &= 700{,}000 \text{ SEK/manSv} \cdot 1.13 \text{ manSv} - 5.8 \text{ MSEK} \\ &= -5.01 \text{ MSEK} \end{aligned}$$

Evacuation of pregnant women is **not** justified based on radiological protection factors of risk reduction and monetary costs alone. Evacuation is justified only if the monetary value assigned to the unit collective dose is higher than 5 Million SEK.

The average cost of evacuating occupationally active pregnant women for 14 days has been estimated to be around 11,600 SEK/person. The IL for the introduction of evacuation for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{11{,}600 \text{ SEK/14 d}}{7{,}000 \text{ SEK/Sv}} \cong 1{,}500 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_2 = \mathbf{\frac{11{,}600 \text{ SEK/14 d}}{140{,}000 \text{ SEK/Sv}} \cong 80 \text{ mSv/14 d}}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{11{,}600 \text{ SEK/14 d}}{700{,}000 \text{ SEK/Sv}} \cong 20 \text{ mSv/14 d}$$

The averted average individual dose by evacuating a pregnant woman and her unborn child is 2 x 1.12 mSv/14 d (see Sect. 2.3), which is far below the calculated values of $\dot{E}_{opt}$. Therefore, evacuation of pregnant women is not justified for any of the considered α-values.

All mothers and their children

The averted collective dose by evacuating all women and their children (15,000 people) for 14 days is 16.8 manSv and the total cost is 49 Million SEK. The net benefit, B, will be:

$$B_1 = 7,000 \text{ SEK/manSv} \cdot 16.8 \text{ manSv} - 49 \text{ MSEK}$$
$$= -48.88 \text{ MSEK}$$

$$\mathbf{B_2 = 140,000 \text{ SEK/manSv} \cdot 16.8 \text{ manSv} - 49 \text{ MSEK}}$$
$$\mathbf{\simeq -46.65 \text{ MSEK}}$$

$$B_3 = 700,000 \text{ SEK/manSv} \cdot 16.8 \text{ manSv} - 49 \text{ MSEK}$$
$$= -37.24 \text{ MSEK}$$

Evacuation of mothers and their children is not justified based on radiological protection factors of risk reduction and monetary costs alone. Evacuation is justified only if the monetary value assigned to the unit collective dose is higher than 3 Million SEK.

The average cost of evacuating a mother and her two children for 14 days has been estimated to be around 9,800 SEK. The IL for the introduction of evacuation for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{9,800 \text{ SEK/14 d}}{7,000 \text{ SEK/Sv}} \cong 1\,500 \text{ mSv/14 d}$$

$$\mathbf{\left(\dot{E}_{opt}\right)_2 = \frac{9,800 \text{ SEK/14 d}}{140,000 \text{ SEK/Sv}} \cong 70 \text{ mSv/14 d}}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{9,800 \text{ SEK/14 d}}{700,000 \text{ SEK/Sv}} \cong 10 \text{ mSv/14 d}$$

The averted individual dose for a mother and her two children by evacuation for a period of 14 days is far below the calculated values of $\dot{E}_{opt}$. Therefore, evacuation of mothers and their children is not justified for any of the considered α-values.

Occupationally active mothers and their children

The average cost of evacuating occupationally active mothers and their children has been estimated to be around 14,800 SEK. The IL for the introduction of evacuation for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{14,800 \text{ SEK/14 d}}{7,000 \text{ SEK/Sv}} \cong 2,000 \text{ mSv/14 d}$$

$$\mathbf{\left(\dot{E}_{opt}\right)_2 = \frac{14,800 \text{ SEK/14 d}}{140,000 \text{ SEK/Sv}} \cong 100 \text{ mSv/14 d}}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{14,800 \text{ SEK/14 d}}{700,000 \text{ SEK/Sv}} \cong 20 \text{ mSv/14 d}$$

The averted individual dose for a mother and her two children by evacuation for a period of 14 days is far below the calculated values of $\dot{E}_{opt}$. Therefore, evacuation of ocupationally active mothers and their children is not justified for any of the considered α-values.

Non-occupationally active mothers and their children

The average cost of evacuating non-occupationally active mothers and their children has been estimated to be around 4,800 SEK. The IL for the introduction of evacuation for 14 days can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{4,800 \text{ SEK/14 d}}{7,000 \text{ SEK/Sv}} \cong 700 \text{ mSv/14 d}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{\mathbf{4,800 \text{ SEK/14 d}}}{\mathbf{140,000 \text{ SEK/Sv}}} \cong \mathbf{30 \text{ mSv/14 d}}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{4,800 \text{ SEK/14 d}}{700,000 \text{ SEK/Sv}} \cong 7 \text{ mSv/14 d}$$

The averted individual dose by evacuation for a period of 14 days is far below the calculated value of $\dot{E}_{opt}$. Therefore, evacuation of non-occupationally active mothers and their children is not justified for any of the considered α-values.

3.1.4. Relocation in the Long-Term Phase

The averted individual doses by relocation in the beginning of the long-term phase is around 0.5 mSv/month. The cost per person for relocation is 15.300 SEK/month taking into consideration accomodation costs (2.000 SEK/month) and lost job (13,300 SEK/month) (see Section 2.4).

Relocation with loss of job

The net benefit, B, of relocating one individual in the long-term phase if the job is lost will be:

$$\begin{aligned} B_1 &= 7,000 \text{ SEK/manSv} \cdot 0.0005 \text{ Sv/month} - 15.300 \text{ SEK/month} \\ &= -15,297 \text{ SEK/month} \end{aligned}$$

$$\begin{aligned} \mathbf{B_2} &= \mathbf{140,000 \text{ SEK/manSv} \cdot 0.0005 \text{ Sv/month} - 15,300 \text{ SEK/month}} \\ &= \mathbf{-15,230 \text{ SEK/month}} \end{aligned}$$

$$\begin{aligned} B_3 &= 700,000 \text{ SEK/manSv} \cdot 0.0005 \text{ Sv/month} - 15.300 \text{ SEK/month} \\ &= -14,950 \text{ SEK/month} \end{aligned}$$

Relocation is **not** justified based on radiological protection factors of risk reduction and monetary costs alone. Relocation is justified only if the monetary value assigned to the unit collective dose is higher than 30 Million SEK.

The IL for the introduction (and withdrawal) of relocation for optimum protection expressed as averted effective individual dose per unit time, $\dot{E}_{opt}$, can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{15,300 \text{ SEK/month}}{7,000 \text{ SEK/Sv}} \cong 2,000 \text{ mSv/month}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{\mathbf{15{,}300\ SEK/month}}{\mathbf{140{,}000\ SEK/Sv}} \cong \mathbf{100\quad Sv/month}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{15{,}300\ \text{SEK/month}}{700{,}000\ \text{SEK/Sv}} \cong 20\ \text{mSv/month}$$

The averted individual dose per unit time by relocating people in the long-term phase of around 0.5 mSv/month is below the calculated values of $\dot{E}_{opt}$ for all the considered α-values, and relocation is therefore not justified.

<u>Relocation without loss of job</u>
The net benefit, B, of relocating one individual in the long-term phase if the job not is lost will be:

$$\begin{aligned} B_1 &= 7{,}000\ \text{SEK/manSv} \cdot 0.0005\ \text{Sv/month} - 2{,}000\ \text{SEK/month} \\ &= -1{,}997\ \text{SEK/month} \end{aligned}$$

$$\begin{aligned} \mathbf{B_2} &= \mathbf{140{,}000\ SEK/manSv \cdot 0.0005\ Sv/month - 2{,}000\ SEK/month} \\ &= \mathbf{-1{,}930\ SEK/month} \end{aligned}$$

$$\begin{aligned} B_3 &= 700.000\ \text{SEK/manSv} \cdot 0.0005\ \text{Sv/month} - 2{,}000\ \text{SEK/month} \\ &= -1{,}650\ \text{SEK/month} \end{aligned}$$

Relocation is **not** justified based on radiological protection factors of risk reduction and monetary costs alone. Relocation is justified only if the monetary value assigned to the unit collective dose is higher than 4 Million SEK.

The IL for the introduction (and withdrawal) of relocation for optimum protection expressed as averted effective individual dose per unit time, $\dot{E}_{opt}$, can be calculated to be:

$$\left(\dot{E}_{opt}\right)_1 = \frac{2{,}000\ \text{SEK/month}}{7{,}000\ \text{SEK/Sv}} \cong 300\ \text{mSv/month}$$

$$\left(\dot{E}_{opt}\right)_2 = \frac{\mathbf{2{,}000\ SEK/month}}{\mathbf{140{,}000\ SEK/Sv}} \cong \mathbf{10\ mSv/month}$$

$$\left(\dot{E}_{opt}\right)_3 = \frac{2{,}000\ \text{SEK/month}}{700{,}000\ \text{SEK/Sv}} \cong 3\ \text{mSv/month}$$

The averted individual dose per unit time by relocating people in the long-term phase is below the calculated values of $\dot{E}_{opt}$ for all the considered α-values, and relocation is therefore not justified.

3.1.5. Decontamination in the Long-Term Phase

Experiments with decontamination of urban surfaces and experience from the Chernobyl accident indicate that a realistic large scale reduction factor is not higher than 2. If it is assumed that a large scale decontamination campaign can be carried out with a two-fold reduction of the external dose rate, the individual external dose **averted** in a lifetime of 70 years will be of the order of 60 mSv per person over this period.

Decontamination can be a fairly costly process. Decontamination is justified if the cost is less than the monetary value of the collective dose averted. Cost estimates for decontamination have ranged between 1.000 $ and 10.000 $ per person depending on the population density in the area to be contaminated [4]. The averted lifetime dose of 60 mSv is equivalent to a monetary value of 60 $, 1.200 $ and 6.000 $ for the three α-values, respectively, implying that a large scale decontamination would be justified only if the decontamination efficiency is a factor of 2 or more, and then only for very high and unrealistic monetary values assigned to the unit collective dose.

3.1.6. Milk Restrictions

The potential collective effective dose per unit mass of milk is proportional to the concentration of the radionuclide in the milk, C, and the committed effective dose per unit activity intake, e [3]:

$$S = C \cdot e \tag{5}$$

The optimized Intervention Level (IL) expressed as activity concentration in the milk/milk product can be calculated from the cost per unit mass of milk, b, and the collective effective dose per unit mass of milk, S:

$$\alpha \cdot S - b = 0 \tag{6}$$

$$\alpha \cdot C \cdot e - b = 0 \Rightarrow \tag{7}$$

$$C_{opt} = \frac{b}{\alpha \cdot e} \tag{8}$$

The meaning of C_{opt} is that restrictions should be introduced when the activity concentration in milk, C, is greater than C_{opt} and be terminated when $C < C_{opt}$.

The cost of milk/milk products is assumed to be 7 SEK/kg [3], and the averted collective effective dose in the year following the accident, if the milk is removed from human consumption, is assumed to be 0.02 manmSv/kg (see Sect. 2.5). The net benefit, B, can therefore be calculated to be:

$$\begin{aligned} B_1 &= 7,000 \text{ SEK/manSv} \cdot 0.00002 \text{ manSv/kg} - 7 \text{ SEK/kg} \\ &= -6.86 \text{ SEK/kg} \end{aligned}$$

$$\begin{aligned} \boldsymbol{B_2} &= \textbf{140,000 SEK/manSv} \cdot \textbf{0.00002 manSv/kg} - \textbf{7 SEK/kg} \\ &= \textbf{-4.20 SEK/kg} \end{aligned}$$

$$\begin{aligned} B_3 &= 700,000 \text{ SEK/manSv} \cdot 0.00002 \text{ manSv/kg} - 7 \text{ SEK/kg} \\ &= 7 \text{ SEK/kg} \end{aligned}$$

Milk restriction is justified only in case 3 with the "high" α-value where the net benefit is positive.

The IL for the introduction (and withdrawal) of measures for optimum protection in form of removing the milk from human food can be calculated to be:

$$\left(\dot{C}_{opt}\right)_1 = \frac{7\ \mathrm{SEK/kg}}{7{,}000\ \mathrm{SEK/Sv} \cdot 12.5\ \mathrm{nSv/Bq}} = 80{,}000\ \mathrm{Bq/kg}$$

$$\left(\dot{C}_{opt}\right)_2 = \frac{7\ \mathrm{SEK/kg}}{140{,}000\ \mathrm{SEK/Sv} \cdot 12.5\ \mathrm{nSv/Bq}} = 4{,}000\ \mathrm{Bq/kg}$$

$$\left(\dot{C}_{opt}\right)_3 = \frac{7\ \mathrm{SEK/kg}}{700{,}000\ \mathrm{SEK/Sv} \cdot 12.5\ \mathrm{nSv/Bq}} = 800\ \mathrm{Bq/kg}$$

The potential averted collective dose for the first year is assumed to be 0.02 man-mSv/kg (see Sect. 2.5). This value corresponds to an activity concentration of 1,600 Bq/kg. Therefore, milk restriction is justified only in case 3 as also determined from the net benefit, $B_3 > 0$.

3.2 International Guidance

No clear consensus has yet emerged internationally on the most appropriate quantity to use for expressing intervention levels of dose. What is absolutely clear however is that, when making judgements on relocation or any other protective measure, it is the dose averted that has to be balanced against the costs and any other dis-benefits of taking the measure. Consequently, criteria expressed in any other terms can only be surrogates for the dose averted.

There are considerable, if not insupearble, difficulties associated with the formulation of fairly precise, yet generally applicable, quantitative guidance on relocation in terms of averted dose or indeed any other quantity. The quantity, dose rate (which is not the same as dose in a year), offers the greatest potential in this context. Judgements on the optimum level of averted dose at which relocation should be implemented would, in general, depend on the period over which the dose was averted and for which the relocation was foreseen. For example, different judgements could be expected where relocation of say several months and tens of years, respectively, were required to avert the same level of dose.

If the quantity, dose in a year, is used as a surrogate for the dose averted, this is consistent with the principles of intervention. Despite its extensive use for the purposes of formulating criteria for relocation (the current IAEA guidance [1] is expressed in these terms), there are negative aspects of its use. Conceptually, there are no compelling reasons for choosing one year as the time period of reference in preference to any other period; indeed there may be strong arguments to the contrary.

Familiarity and the use of this period for the purposes of expressing many other quantities may have been instrumental in its choice. The latter, however, is responsible for the main problem with this quantity, that is the possibility of it being misinterpreted. This arises because direct comparison, however inappropriately, can be readily made with annual dose limits and erroneous conclusions drawn.

One area where there has been much confusion over the role of dose limits in determining intervention has been the imposition of foodstuff restrictions in the longer term following an accident and at distances far from the release. It has been argued that, because exposures from contaminated foodstuffs are controllable (i.e. by restricting their production or consumption), they should be subjected to the full system of dose limitation, including the application of the dose limits recommended by the ICRP. This, however, represents a misinterpretation of the intent of ICRP's recommendations.

Despite the problems with the present international guidance on intervention levels, the current indicative guidance from the IAEA is presented below for the protective measures under consideration: sheltering, evacuation, food restrictions and relocation. For each protective measure a range of intervention levels is given, in principle emerging from an optimization process and reflecting the characteristics of the accident, the local environmental conditions and the severity of the protective measure itself:

Sheltering:	**A few to a few tens of mSv in the first 24 hours**
Evacuation:	**Ten to a few hundred mSv in the first 24 hours**
Food control:	**One to a few tens of mSv committed from annual intakes for each of seven main categories of foodstuffs**
Relocation:	**A few to a hundred of mSv over a year**

The international guidance on **realism** in the application of intervention is clear. In general, the criteria should be applied to an average member of the group affected by the protective measure and the estimate of the dose averted should be as **realistic** as possible. The adoption of cautious approaches of dose assessment will inevitable result in action being taken that is sub-optimal and contrary to the principles and purposes of intervention.

4 Conclusions

The results of the justification/optimization calculations for different protective measures are summarised in the Table below. For each protective measure, three different results are given, corresponding to three different monetary values of the unit collective dose used (1,000 $/manSv, 20,000 $/manSv and 100,000 $/manSv). Also shown in the Table are the individual doses averted by the protective measures.

The individual doses averted by evacuation in the secondary phase are below the lower value of intervention level range for evacuation given in the indicative guidance from the IAEA.

The individual doses averted by relocation in the long-term phase of about 6 mSv/year are above but close to the lower value of the range of intervention level given in the indicative guidance from the IAEA. According to the IAEA, the indicative nature of the guidance is such that it must not be taken to preclude values outside the specified range. In addition, it would be erroneous to select arbitrarily values from the bottom of the range of levels. Consequently, for relocation of large urban areas like Visby, the optimum value of intervention will probably fall outside the range at the top level as also indicated by the optimization calculations in Section 3.1.4. The reason is the disruptive character [5] and major costs of relocation.

The collective dose averted by milk restrictions will be about 0.02 manmSv/kg milk the first year after the accident. With an individual consumption rate of 175 kg milk per year, the average individual dose would be about 4 mSv/y. This dose level is also close to the lower value of the intervention level range given in the indicative guidance from the IAEA for a single main food category.

The individual doses from the postulated accident that would have contaminated the island of Gotland are, for the primary and secondary phases, of a magnitude that would **not** call for intervention in form of sheltering and evacuation.

The rate of dose accumulation (0.5 mSv/month) from deposited cesium with a contamination density of ^{137}Cs of the order of 1 - 2 MBq/m^2 is of the same order of magnitude as in the highest contaminated areas in the USSR caused by the Chernobyl accident. The conclusion of the **International Chernobyl Project** with respect to the most contaminated areas was that relocation is not necessary because the average doses that could be potentially averted would be of the same order as or less than the doses due to average natural background radiation.

Consequently, even if the estimated external doses in the city of Visby from deposited ^{137}Cs is of the order of 2 mSv/year in average over 70 years, ie. equal to the annual average doses in the most contaminated areas in the USSR, the conclusion is that no relocation should be introduced in the city of Visby or elsewhere at the island in the long-term phase because the extra incremental individual risk is of the order of about 1 in 10.000 per annum. This additional risk, while not trivial, is marginal in comparison with risks experienced in everyday life and in itself would not justify such a radical measure as relocation.

Intervention Levels for Exercise Sievert Gotland			
Sheltering primary phase	**Averted dose**	**IL**	**Justification**
Total population	0.17 mSv/15 h	10 mSv/15 h	not justified
		0.4 mSv/15 h	not justified
		0.1 mSv/15 h	justified
Those working at night	0.17 mSv/15 h	150 mSv/15 h	not justified
		7 mSv/15 h	not justified
		1 mSv/15 h	not justified
Sheltering secondary phase	**Averted dose**	**IL**	**Justification**
Pregnant women	0.25 mSv/14 d	1.500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
All mothers and their children	3 x 0.25 mSv/14 d	700 mSv/14 d	not justified
		40 mSv/14 d	not justified
		7 mSv/14 d	not justified
Mothers working at night and their children	3 x 0.25 mSv/14 d	1.500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
Evacuation secondary phase	**Averted dose**	**IL**	**Justification**
Pregnant women	1.12 mSv/14 d	1.500 mSv/14 d	not justified
		80 mSv/14 d	not justified
		20 mSv/14 d	not justified
All mothers and their children	3 x 1.12 mSv/14 d	1,500 mSv/14 d	not justified
		70 mSv/14 d	not justified
		10 mSv/14 d	not justified
Occupationally active mothers and their children	3 x 1.12 mSv/14 d	2,000 mSv/14 d	not justified
		100 mSv/14 d	not justified
		20 mSv/14 d	not justified
Non-occupationally active mothers and their children	3 x 1.12 mSv/14 d	700 mSv/14 d	not justified
		30 mSv/14 d	not justified
		7 mSv/14 d	not justified
Relocation late phase	**Averted dose**	**IL**	**Justification**
With loss of job	0.5 mSv/month	2,000 mSv/month	not justified
		100 mSv/month	not justified
		20 mSv/month	not justified
Without loss of job	0.5 mSv/month	300 mSv/month	not justified
		10 mSv/month	not justified
		3 mSv/month	not justified
Milk restrictions late phase	**Averted dose**	**IL**	**Justification**
Total population	0.02 manmSv/kg	80 kBq/kg	not justified
		4 kBq/kg	not justified
		0.8 kBq/kg	justified

The individual doses averted by sheltering, both during the primary and the secondary phases, are below the lower value of the intervention level range for sheltering given in the indicative guidance from the IAEA.

5 References

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Annex II. Multi-Attribute Utility Analysis

by

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1 Introduction

This annex provides applications on how multi-attribute utility analysis can be used when planning protective actions. Generally, the aim of a decision-aiding technique, including utility analysis is to help to analyze the decision problem by providing a mathematical method for comparing and ranking the actions, and most importantly, by bringing more insight and understanding into decisions; to render explicit what factors and numbers are important and what are the consequences of an action. Those interested in the theory of decision and utility analysis may consult the literature (Fr88, Wi86, Ke76).

In order to translate the verbal descriptions of a decision problem into a mathematical model the problem has to be broken down into small pieces that can be dealt with individually and then recombined logically. In formulating the problem a clear distinction is made between the choices that can be made (*the actions*), the characteristics of the actions (*the attributes*) and the relative desirability of the different sets of characteristics (*preferences*). The important part of the analysis, the structuring of a problem, is described carefully in the examples presented below.

It is worth noting that the protective actions to be analyzed and ranked in this document are base cases which probably can be replaced by more carefully planned - fine tuned - actions. For example for a single protective problem there might be a combination of actions or certain subgroups of population for whom a specified action will be justified. The scope of this study is not to find the best actions, but to present a method for ranking the actions and evaluating intervention levels. If new, feasible actions are identified the analysis should be revised. It should be noted that if new actions are defined the ranking of original actions is not changed.

In utility analysis the evaluation of alternatives is commonly performed by means of *additive utility functions*. The existence of additive utility functions is normally verified during the analysis - and should, in principle, be verified. In this example we assume that the analysis can be performed by additive utility functions and that their existence is verified (Ke86, Si91).

2.1 Sheltering in the Primary Phase

The first step in the analysis is the identification of the protective actions which could be taken. In the primary phase the actions considered are *sheltering of all inhabitants* and *no-action,* accepting the status quo.

Attributes in decision analysis are the variables that are used for comparing the actions. All actions are represented as levels of k attributes:

$$a = (a_1, a_2, \dots a_k),$$

where a_i is the level of action a on i:th attribute. In the primary phase in this example the attributes considered important when a making decision on sheltering are the *health detriment* caused by dose and the *monetary costs* of sheltering. The health detriments caused by radiation are measured as a collective dose. The values of dose attribute in the various actions are between 4.14 and 414 manSv due to the uncertainty associated with the prediction of dose (Table BI, cf. Section 4.1). The scale of dose to be used in the calculation is 0 - 500 manSv. Correspondingly, the scale of costs attribute is 0 - 3.4 million SEK. The utility analysis of sheltering is based on the decision Table BI.

As mentioned in Section 3.1 the uncertainty of

Table BI. Decision table of the early protective actions. In parentheses doses are given in manSv and the costs of actions in million SEK (manSv, MSEK).

	Fall-out level			
	Low		Projected	High
No action	(4.14, 0)	(41.4, 0)	(414, 0)	
Sheltering	(3.19, 3.4)	(31.9, 3.4)	(319, 3.4)	
		Probabilities		
	0.3	0.6		0.1

the dose estimate is described by assessing the probability of 0.6 on the best estimate of dose and the probabilities of 0.3 and 0.1 on the values that are, by a factor of 10, lower or higher, respectively, given as the fall-out levels in the table BI.

The uncertainty associated with the predicted dose has to be assessed in the real situation and it will influence the intervention level.

The values of attributes in various actions, as well as the preferences of a decision maker connected to the levels of attributes, are converted by a utility function to common units called utility, normally between zero and one (see Section 5.5). The most preferred level of an attribute is assigned a utility of one, the least preferred level is assigned a value of zero. The intermediate values are assessed by the utility function. The simplest conversion is a straight line, where a unit change in the value of an attribute corresponds to an equal change in utility.

By definition, the utility function u(.) represents a decision maker's preferences between the values a and b:

$$u(a) \geq u(b),$$

if, and only if, he holds a at least as good as b. Note, in group decisions - in social choices - at least in a democracy, the decision maker(s) represents the population, on behalf of whom the decision is made, its preferences which are expected to be considered in a fair and just solution.

The single-attribute utility functions for the dose and costs attributes have been assessed by a method called the reference experiment (Ke77, Fr88, Sm89, Si91). In the reference experiment e.g. the following two hypothetical options are given to the decision maker:

Option A: the dose is 0 manSv with a probability of 0.4 or, otherwise, the dose is 500 manSv with a probability of 0.6.

Option B: The dose is 250 manSv for certain.

If the decision maker is indifferent between options A and B, and we have chosen u(0 manSv) = 1.0 and u(500 manSv) = 0, then, according to the theory, u(250 manSv) = 0.4.

In other words the change in dose from 500 manSv to 200 manSv is equally preferred to the change from 200 manSv to zero manSv i.e. he/she always prefers entering a lottery to receiving a dose equal to its expected value. This implies a *risk seeking attitude*. Generally, the attitude toward risk results in a threat of defeat connected to the decision. In this case there is a threat of loss of money or an increased risk of health detriment (Ka82, Si91).

By fitting a commonly used exponential function to the defined points, the assessed single-attribute utility functions are $u_s(s)$ for the dose attribute and $u_c(c)$ for the costs attribute, respectively:

$$u_s(s) = 1.78e^{-0.0016s} - 0.78$$
$$u_c(c) = 1.78e^{-0.24c} - 0.78$$

The assessed utility function for dose is shown in Figure B1.

In the introduction we have assumed that the utility of a protective action can be represented by the additive utility function:

$$u(a) = \Sigma_i \, k_i \, u_i(a_i), \qquad (B1)$$

where $u_i(a_i)$ are single-attribute utility functions assessed above. The constants k_i are introduced to bring the total utility of an action (a) onto a

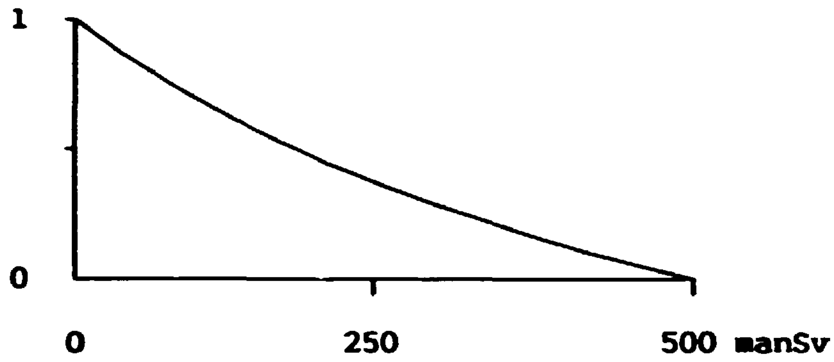

Figure B1. The assessed utility function for dose.

common scale, between zero and one. A more important role of these constants is that they represent the judgement of the decision maker on the relative importance of the levels of dose and cost attributes. *Swing weighting* is an assessment method for scaling constants. The decision maker is asked to compare a pair of hypothetical actions which differ only in their values along two attribute scales. In the assessment the real values of the attributes are used instead of utilities connected to these values. If there are more than two attributes other attributes are fixed to their nominal level during the assessment. In the method a set of hypothetical options is given to the decision maker until an indifferent pair of options is found. For example:

Option A: The collective dose is 250 manSv and the monetary costs are 0.6 MSEK.
Option B: The collective dose is 230 manSv and the monetary costs are 3.4 MSEK.

If the options A and B are indifferent to the decision maker it can be seen that the decision maker is willing to invest 2.8 MSEK to reduce the collective dose by 20 manSv, i.e. the trade-off value - the value of α - is 140 000 SEK/manSv.

When assessing the trade-off value it is important to secure that apart from pure costs and dose other factors are not mixed or considered in the assessment. If other factors are felt important they should be added to the attribute list. Also generally, decision analysis does not require an accurate trade-off value but a range; the minimum and the maximum investment in order to reduce radiation risks. A rough mean value could be used in the analysis and the effect of its uncertainty is studied afterwards in *a comprehensive sensitivity analysis*. The demand for a relative narrow range of a trade-off value is based on the fact that the decision maker must be striving for a just and fair decision.

To gain insight in the assessment of the trade-off value several methods presented in literature can be used of which I would like to mention the '*human capital*'- and '*willingness to pay*' principles. Also a consideration of the amount of money currently invested by society in reducing non-radiological risks, e.g. avoiding a fatal cancer, render the judgement, should it be in harmony with the investments in radiation protection.

It is expected that the state will not reimburse the costs of sheltering, but the costs are paid for by the households. To reach a fair and just decision the population's own trade-off value also has to be determined. A fair and just decision could also be attributed to the population's acceptance of a protective action.

The 'willingness to pay' principle is apparently a useful indicator of the trade-off value when an individual is protecting his own health or life. When a man's health is at risk and he himself pays for his own safety, he should also be allowed to make his own decision.

Although the population might accept the average cost of sheltering, 60 SEK/person even in low doses, the trade-off value should not be based on the population's acceptance of low costs. This might lead to inconsistencies with other protective actions and to irrational behaviour.

In this study it was decided to use the trade-off value of 140 000 SEK/manSv as a central value - as a rough mean value - and that the sensitivity analysis should be performed to the relatively wide range of the α-value of 7 000 - 700 000 SEK/manSv.

By using the trade-off value of 140 000 SEK/manSv the decision maker is willing to invest 3.4 million SEK in order to decrease the dose by 24.3 manSv, e.g. from 500 manSv to 475.7 manSv. Thus, for him, the following hypothetical actions are indifferent

(0 MSEK, 500 manSv) and
(3.4 MSEK, 475.7 manSv). (B2)

Substituting B2 to formula B1 (generally, no matter if the utility function is additive or multiplicative) and using the definitions $u_s(0) = u_c(0) = 1$ and $u_s(500) = u_c(3.4) = 0$, we get $k_s u_s(475.7) = k_c u_c(0)$. From the assessed single-attribute utility function for dose we get $u_s(475.7) = 0.05$ and thus $k_c = 0.05k_s$. We have assumed that the analysis can be performed by additive utility functions, then $k_c + k_s = 1$, and $k_c = 0.05$ and $k_s = 0.95$.

The utility function that has been normalised between zero and one is:

$$u(s,c) = 0.95(1.78e^{-0.0016s} - 0.78) + 0.05(1.78e^{-0.24c} - 0.78).$$

Because there are uncertainties linked to a decision i.e. the attribute levels are defined in terms of probabilities the sum to be calculated is called the *expected utility:*

$$\Sigma_j i p(a_i)\, k_j u_j(a_{ij}),$$

where the probability $p(a_i)$ is the occurrence of a certain attribute j level i, and $\Sigma_i p(a_i) = 1$, by definition. The probability information is used to define a certain or non- probability level that should be equally preferred to the probability distribution. The calculated certainty equivalent values are 58.0 manSv for no action and 46.1 manSv for sheltering. The expected utility is defined so that the decision maker's most preferred alternative has the maximum expected utility.

The expected utility $E = \Sigma_i p_i u(s_i, c_i)$ can now be calculated for different countermeasures, where p_i are the probabilities of fall-out levels. Based on the figures presented above, the calculated utilities are:

no action: 0.85
sheltering: 0.83.

It is wise to take the ranking of the countermeasures with these figures with a pinch of salt if the variations of judgmental input are not analyzed with a sensitivity analysis. We have to estimate what influence the chosen trade-off value between dose and cost, the variation in utilities i.e. the shape of utility functions, and the variation in the probabilities of fallout levels all have on the ranking of actions. The sensitivity analysis currently used and implemented here examines the effects of varying one parameter at a time. The calculations were performed by a computer program (Sm89) and the results are briefly described below.

When assessing the influence of the trade-off value between dose and costs to the decision, an interesting piece of information is to find *the break-even value* i.e. the value of α, when the ranking of actions is changed. The calculated break-even «CHAR E0» -value is nearly 300 000 SEK/manSv which is in the range of 7 000 - 700 000 SEK/manSv determined in this study. Thus the ranking depends on the value of α and - in principle - because of determined wide range of α the sheltering is justified.

By choosing linear utility functions instead of risk[1] prone ones does not affect the ranking of actions. By linear, risk neutral utility functions no-action is slightly more preferred to sheltering when comparing the actions with risk prone functions. On the contrary, if the decision maker is more risk seeking than assumed above, the utility of sheltering will be slightly more close to the utility of no-action but the ranking of actions is not changed. The effect of the probabilities of fallout levels has a stronger influence on the ranking of actions. If the probabilities are changed from 0.3, 0.6, 0.1 (low fallout, projected fallout, and high fallout, respectively) to 0.1, 0.6, 0.3 we are near the break- even point. Thus the predicted dose and the probabilities of fallout levels are important factors in considering the actions to be taken, but to a much lesser extent than the trade-off value.

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[1]Here risk means a decision maker's attitude to risk as is defined by the utility theory and modelled by the shape of a utility function.

Using the central trade-off value 140 000 SEK/manSv and by assuming that the projected average individual dose to people staying outdoors during 15 hours' plume passage was predicted to be 3.7 mSv instead of 1.85 as assumed in the example (Section 3.1) we would be near the break-even point. The decision maker would then choose sheltering. Then the area-and-accident specific intervention level for sheltering the whole population would be 3.7 mSv accumulated during 15 hours corresponding to the outside dose. The range of intervention level corresponding to the range of trade-off value of 7 000 - 700 000 SEK/manSv is then 0.2 - 20 mSv.

2.2 Sheltering and Evacuation in the Secondary Phase

In the secondary phase the following actions are considered to mitigate the accident consequences: no-action, sheltering of pregnant women and children up to the age of 14 years in their homes for 14 days, or the same group of pregnant women and children are evacuated for a period of 14 days to areas where the dose rate is 10% of the dose rate at Gotland.

The attributes which are considered to affect the decision are: *the monetary costs* of the countermeasures, the *individual dose*, and the *stress* caused by evacuation or long period sheltering. The costs of the various actions are shown in Table BIII (c.f. section 4.2 - 4.3). Based on figures presented in the tables BII and BIII the scale to be used in the calculation is: 0 - 10 000 SEK, and for

Table BII. The cumulative dose distributions in various measures as well as the outdoor gamma dose distribution. The individual dose to a given percentage of the population is less than or equal to the corresponding dose (mSv).

Actions	Percentage of population 10%	95% (mSv)	100%	Certainty equivalent
Outdoor dose	2	6	10	3.9
No action	0.6	1.9	3.1	1.2
Sheltering	0.5	1.5	2.5	0.97
Evacuation	0.06	0.19	0.31	0.12

dose: 0 - 10 mSv, respectively. The estimated individual outdoor gamma dose distribution and also the individual gamma dose distribution for various actions are shown in Table BII.

In utility analysis it is possible to use *the distribution of an attribute* instead of its mean value. This is demonstrated in this example by replacing the collective dose by the individual dose distribution. The certainty equivalent given in Table BII is the same as the population weighted mean dose. The use of a mean value or distribution depends on the easiness in assessing the mean value or distribution. This is true with risk neutral utility functions. With risk prone utility functions the certainty equivalent values are lower indicating that e.g. the lower dose values are more preferred than the high ones.

Warning time for the accident in question is short. There is not enough time for organizing transportation, accommodation for evacuees or the arrangements of evacuation localities and motivation of their inhabitants. Neither is there time enough for proper timing of the evacuation nor appropriate information. The limited time period to implement evacuation neglects human considerations and causes stress. The most important factors affecting the forming of stress are: Information, proper timing, voluntariness of evacuation, and adaptation to new surroundings (Er92, Va82). Long-term sheltering - staying indoors for 14 days - will also cause food, social and medical problems for all the sheltered people which in this example are associated to the stress factor.

In this example it is assumed that one third of the evacuees and one tenth of the people in the evacuation localities are experiencing stress for 14 days. The estimated number of stressed people is 6000, corresponding to 230 »man years of stress«. When sheltering is considered all sheltered and some of their relatives are experiencing stress. The estimated number is 17 000 people corresponding to 650 man years of stress. The stress is here assumed to be caused by sheltering or evacuation, and thus if no-action is chosen no stress is experienced. The scale of the stress attribute used is 0 - 650 man years.

By giving the mean values for individual dose and costs the values of attributes in various actions are as is given in Table BIII.

Table BIII. The values of attributes in various actions.

	Dose (mSv)	Costs (SEK)	Stress (man y)
No action	1.2	0	0
Sheltering	0.97	5000	650
Evacuation	0.12	9800	230

As a base case the values of attributes are converted to the common scale by linear utility functions. The method is the same in all its essentials as is presented in the example of sheltering in the primary phase. The decision maker's attitude apt to take risk is discussed in connection with the discussion of sensitivity analysis below.

A private person is not willing to pay the costs of sheltering or evacuation, but it is expected that the state will reimburse them. If the reimbursement of the costs and the compensation demands of increased risk caused by radiation are not mixed to the trade-off value between dose and costs, we can use the same range and central trade-off value as in the sheltering example. The central trade-off value between dose and costs is set to 140 SEK/mSv in the calculation.

The ratio of scaling constants k of dose and costs attributes can be assessed in a similar way as is presented in the example of sheltering by setting the stress attribute at some fixed level. The assessment of the relative importance of the stress attribute can be done by selecting either the dose or the costs attribute whose levels will be varied in the trade-off. It is felt that a more natural way is to choose the dose attribute and trade the stress attribute against it.

Apart from the physical detriment a fatal cancer will also cause stress to the patient and to his/her relatives, as an approximation of 10 man years of stress. In this example the expected number of fatal cancer cases in the group to be protected is *one* (1.2 mSv × 15 500 × 0.05 = 0.93).

Excluding the costs from the trade-off, i.e. setting the costs attribute on its nominal - fixed - level, two simplified hypothetical alternatives A and B with a particular level on each of the dose and stress attributes are given to the decision maker:

Option A: Individual dose is 1.25 mSv and the number of stressed man years is zero.

Option B: Individual dose is zero and the number of stressed man years is 100.

In this example, for the sake of simplicity, alternatives A and B are assumed to be equally preferred by the decision maker. If other effects of dose, except stress, are excluded the stress experienced with a fatal cancer is felt much worse by the decision maker than stress experienced with sheltering or evacuation. It should be noted that the figures represented above are not based on any scientific study.

By using the result of the hypothetical alternatives the ratio of scaling constants between the costs, stress and dose attributes can now be calculated. If the sum of scaling the constants is normalised to one the values of k_i:s could be calculated. The calculated scaling constants are $k_{costs} = 0.80$, $k_{dose} = 0.11$, and $k_{stress} = 0.09$.

Based on the figures presented above and using a computer program (Sm89) to make the calculations slightly easier, the calculated expected utilities for various actions are:

no action:	0.99
sheltering:	0.50
evacuation:	0.18

In a sensitivity analysis the effect of the decision maker's risk seeking attitude is verified by using risk prone utility functions for all attributes. The shape of the utility function, for example for costs, is defined so that by substituting 5000 SEK in the function, the utility is 0.4, instead of 0.5 as it is for a risk neutral decision maker. With risk prone functions the calculated utilities are:

no action:	0.98
sheltering:	0.42
evacuation:	0.22

The concaveness of the utility function, i.e. the decision maker(s) risk seeking attitude, has a minor effect on the results. This is due to the smoothness of the utility function and (c.f. Figure 1B), most importantly, to the relative large uncertainties associated with the trade-off values.

No-action is producing much more good than harm compared to sheltering or evacuation. Either changing the trade-off value to a value fifty times greater or increasing man years of stress from 100 to 1000 (see trade-off option B) do not change the ranking of the actions. If both these changes are made at the same time the utility of evacuation is near to no-action. In this case the break-even point is reached if either of these values is increased. Sheltering is never an optimal measure.

The analysis indicates that the projected dose should be high, before the short term evacuation becomes an optimal action. The intervention level for evacuation, using the central trade-off value of 140 SEK/mSv, is 80 mSv. The range of the intervention level is 4 - 400 mSv, corresponding to the range of the trade-off value between dose and cost.

2.3 Milk Restrictions

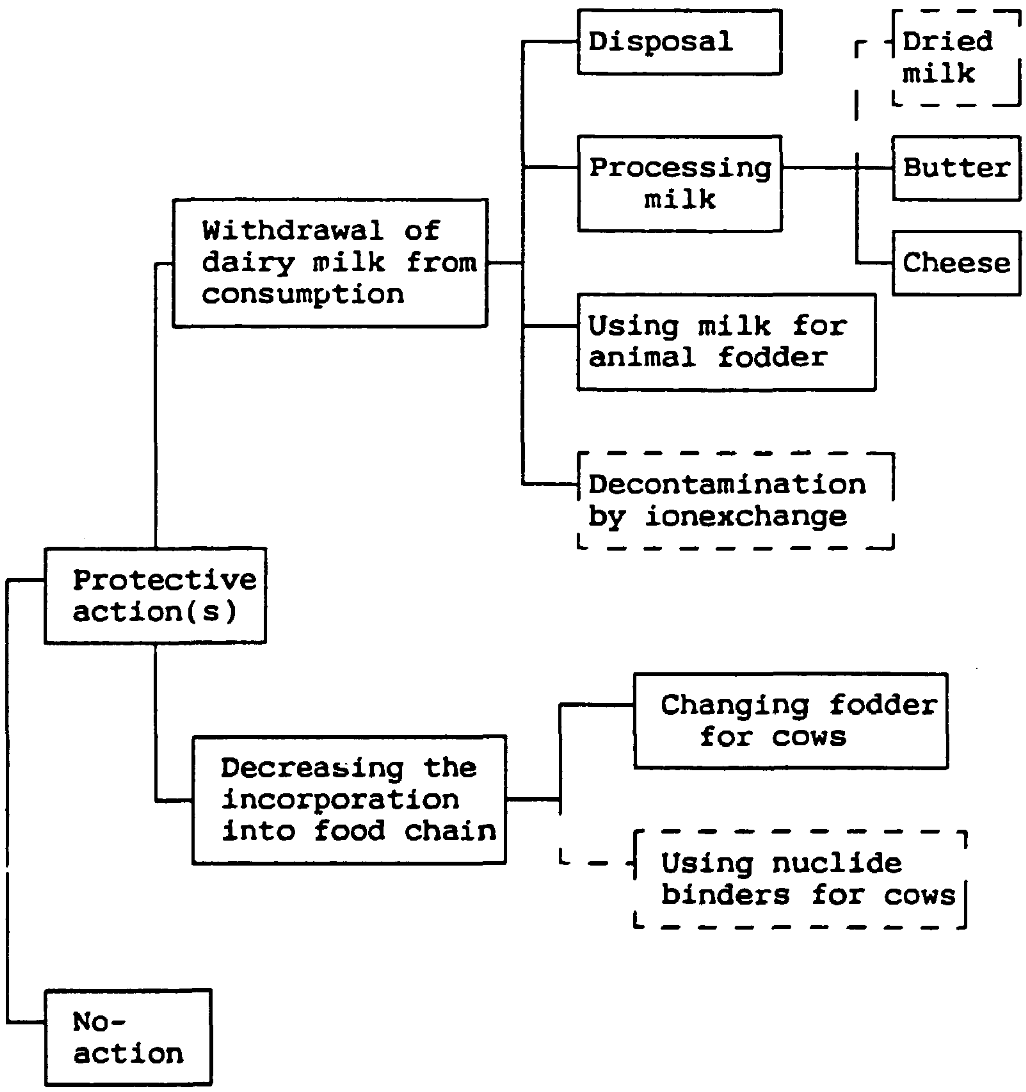
Generally, depending on the accident, different radionuclides might contaminate milk. The protective action to be taken to reduce the dose caused by consuming contaminated milk depends on the radionuclides present. The most important nuclides and those considered also in this example are iodine and cesium. The following protective actions can be considered:

- banning of dairy milk
- making butter and cheese
- changing fodder for cows
- using milk for animal fodder
- using nuclide binders for cows
- decontamination by ionexchange

Only the first three actions can be taken in the early phase of the accident concerned their rapid implementation and the availability of the methods for processing milk.

The decision tree based on the above mentioned actions is shown in Figure B2.

Figure B2. Decision tree for analysis of protective actions for contaminated milk. Actions marked with solid line are considered in the primary phase.



In the decision of protective action the groups of adults, children and infants should be considered separately because of the large variation of the per capita consumption of milk and, thus, the individual dose. This can be done by breaking the dose attribute down into lower level attributes of children and adults, and defining the actions feasible for the whole population. Or, at least in theory, by defining different protective actions for various groups, e.g. for adults and children. However, society is not neutral to the choice of action. In practice it is not easy to formulate the action for one consumer group without affecting the consumption of milk in an other group. Thus the actions in this example are defined on a more generic basis as is presented in the decision tree (Figure B2).

If dairy milk is withdrawn from consumption it is assumed in this example that it is all disposed of as waste or processed to butter and/or cheese.

If the contaminated area is small like Gotland it is also possible to change the fodder for cows. The substitute for grazing or fresh fodder will be grain-based fodder which is assumed to be clean in the first year after the accident. A concentration level in milk comparable to that of the mainland is thus easily obtained.

The importance of considering separately the doses to children and adults is taken into account by breaking the dose attribute down into two lower level attributes of adults and children. In addition to these attributes, the cost of actions is defined as an attribute. The objective hierarchy is shown in Figure B3.

In this example the measured average fallout level in Gotland is as follows:

^{137}Cs	1.5 MBq/m^2
^{134}Cs	0.75 MBq/m^2
^{131}I	2.5 MBq/m^2

It is assumed that adults consume 0.7 l/d of milk on average and children 1.4 l/d. Based on the fallout levels of cesium and iodine the estimated individual dose (committed effective dose) accumulated during one month and during the year following the accident will be as follows (mSv):

	^{131}I	^{134}Cs	^{137}Cs
month	1.6	1.5	2.1
year	1.6	8.2	13.9

The doses calculated above are for adults. The dose caused by ^{137}Cs in the first year corresponds to the mean concentration of 4500 Bq/l during this time period. The total individual dose caused by the above mentioned nuclides for adults is 5.2 mSv in a month and 23.7 mSv in a year, respectively. The calculated total doses for children (ten years old) are 15.8 mSv in a month and 52.8 mSv in a year, respectively.

It is worth noticing that when considering two different timescales there are actually two analyses to be carried out.

If dairy milk is withdrawn from consumption, disposed of and replaced by milk transported from the mainland, the doses will be one tenth of the value mentioned above. In addition to the losses of the production price, 3 SEK/l, the cost of disposing of the milk is assumed to be 20 SEK per 1000 l of milk and the transportation costs 200 SEK/1000 l of milk (Tables BIV and BV).

Figure B3. The hierarchy of objectives.

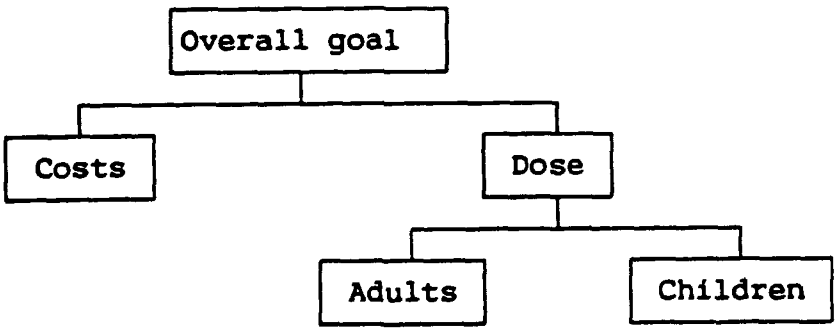


Table BIV. The collective dose in various actions (manSv).

Action	Adults		Children	
	Month	Year	Month	Year
Disposal of dairy milk	24	109	15.8	53
Butter/cheese	33	162	17.5	64
Clean fodder	24	109	15.8	53
No-action	240	1090	158	530

Table BV. The costs of the various actions (million SEK).

Action	Month	Year
Disposal of dairy milk	5.4	65
Butter/cheese	0.37	4.4
Clean fodder	1.7	20
No-action	0	0

As a protective action it is also assumed that all the milk produced at Gotland can be processed to butter and cheese. During the process iodine will be removed by 99% when making butter and by 89.3% when making cheese. Cesium will be removed by 99.2% when making butter and by 94% when making cheese. Only cesium is important in these products and it is estimated that, on average, the cesium concentration is reduced by a factor of 0.04. Because the consumers of butter and cheese are not identifiable the dose is measured as a collective dose. The collective dose caused by butter and cheese is predicted to be 11.7 manSv in a month and 71 manSv in the first year and is assumed to distribute evenly between the various age groups. The dose caused by the dairy milk transported from the mainland is also added to the collective dose in Table BIV.

The extra costs when making butter and cheese are the transportation costs of dairy milk, 200 SEK/1000 l and disposal of costs of skimmed milk and milk whey, 20 SEK/1000 l. It is assumed that there are no extra production costs when changing to the production of butter and cheese at Gotland.

By changing fodder for cows it is assumed that the concentration of milk can be reduced to the same level as in the mainland. It is also assumed that there are enough resources for changing the fodder. The cost of this action is assumed to increase the product price by one SEK/l.

Based on the range of figures given in tables BIV and BV the scale of the dose attribute chosen is 20 - 300 manSv for adults and 10 - 200 manSv for children in a month, and 100 - 1100 manSv for adults and 50 - 600 manSv for children in a year. The scale of the costs attribute is 0 - 6 million SEK in a month and 0 - 70 million SEK in a year. In this example the values of attributes are converted to common units by linear utility functions.

The central trade-off value between an adults' dose and the costs is coherent with the examples above set to 140 000 SEK/manSv. The trade-off value between adults' dose and childrens dose is defined so that one children manSv is twice as important as one adult manSv.

The mathematical part of the analysis was performed by a computer and results are given below. The calculated utilities of various actions are given in Table BVI.

All protective actions as well as their combinations are justified in the first month and year after the accident. The most preferred actions, making butter and/or cheese and changing fodder for cows should be implemented in the first hand so extensively as possible. The actions analyzed here are not intended to be implemented at the same time i.e. changing fodder and making butter simultaneously, but as alternatives.

At the beginning of this example it was assumed that the population will accept the butter and cheese made from contaminated milk. The evidence accumulated during the Chernobyl accident indicates that foodstuffs whose concentration is ten times higher and which are produced in a contaminated area are not accepted by the population. Therefore the action of making butter and/or cheese is not feasible in practice and it is not considered in deriving the intervention level.

Table BVI. The calculated utilities of various actions.

Action	Month	Year
Butter/cheese	0.96	0.95
Clean fodder	0.96	0.94
Disposal of dairy milk	0.92	0.82
No-action	0.27	0.25

The sensitivity analysis performed shows that the ranking of actions does not change within the range of the trade-off value or with risk prone utility functions. The action 'changing fodder' for cows is a truly preferred action. Even if the fallout level is predicted to be twenty times lower in Gotland and in the mainland than was assumed in the example, the action 'clean fodder' is still justified during the first month. During the first year after the accident none of the analyzed protective actions are justified (except making butter/cheese). Disposal of dairy milk is never an optimal action.

The intervention level is assessed by lowering the contamination level so that the break-even point is reached. The intervention level, given as the mean concentration of ^{137}Cs, is 350 Bq/l during the first year after the accident. The intervention level is 200 Bq/l in the first month after the accident given as the mean concentration of ^{137}Cs during the first month. The lower intervention level during the first month is due to a dose mainly caused by iodine. The range of the intervention level corresponding to the range of the trade-off value is 20 - 2000 Bq/l in the first year, and 10 - 1000 Bq/l in the first month. If the disposal of milk is the only feasible action the derived intervention level is 1000 Bq/l.

Conclusion

The aim of this annex has been to demonstrate how multi-attribute utility analysis can be applied when planning protective actions. The actions analyzed are generic and thus not very appropriate for a full analysis of intervention levels. Also the data available in many cases are only indicative, especially those of non-radiological character. However, some general remarks can be concluded.

In the primary phase it was predicted that the projected average individual dose to people staying outdoors during the 15 hours' plume passage would be 1.85 mSv. It was also assumed that the dose averted is proportional to the time spent indoors. However, if the recommendation to shelter is given, sheltering will be slightly more effective than just staying indoors. Sheltering will also bring a relief of stress (which is not modeled in this example) or, at least, gaining the feeling of care. Neither is the decision maker's worry about the high doses of people staying outdoors modeled. Taking these factors into account creates the need to restructure the problem. By including these factors in the analysis we might be near the break-even point, and thus the intervention level for sheltering the whole population will be about 2 mSv accumulated during 15 hours corresponding to an outside dosemeter reading.

In the secondary phase sheltering and evacuation are not justified. The assessed intervention level for short term evacuation is 80 mSv accumulated during 14 days. The range of the intervention level is 4 - 400 mSv, corresponding to the range of the trade-off value between dose and cost.

The intervention level for protective actions concerning milk depends on the time and scale of the accident and thus on the resources. The derived intervention level is assessed by changing the contamination level so low that the break-even point is reached and the ranking of 'clean fodder' and 'no-action' is changed. The intervention level corresponding to the predicted mean concentration of ^{137}Cs is 350 Bq/l in the first year, and 200 Bq/l in the first month after the accident. The range of intervention level is 20 -2000 Bq/l and 10 - 1000 Bq/l, correspondingly.

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Bibliographic Data Sheet **Risø-R-641(EN)**

Title and author(s)

BER-3.2 Report:

Methodology for Justification and Optimization of Protective Measures Including a Case Study:

Protective Actions Planned for Gotland in an »EXERCISE SIEVERT«-Release

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ISBN	ISSN
87-550-1825-4	0106-2840

Dept. or group	Date
Department of Nuclear Safety Research	July 1992

Groups own reg. number(s)	Project/contract no(s)
BER-3.2 (92) 1 Risø-project No. 02471-00	NKS Project BER-3

Pages	Tables	Illustrations	References
50	6	3	17

Abstract (Max. 2000 characters)

This report is a part of the Nordic BER-3 project's work to propose and harmonize Nordic intervention levels for countermeasures in case of nuclear accidents.

This report focuses on the methodology for justification and optimization of protective measures in case of a reactor accident situation with a large release of fission products to the environment.

The down-wind situation is very complicated. The dose to the exposed society is almost unpredictable. The task of the radiation protection experts: To give advice to the decision makers on averted doses by the different actions at hand in the situation - is complicated. That of the decision makers is certainly more: On half of the society they represent, they must decide if they wish to follow the advices from their radiation protection experts or if they wish to add further arguments - economical or political (or personal) - into their considerations before their decisions are taken.

Two analysis methods available for handling such situations: **cost-benefit analysis** and **multi-attribute utility analysis** are described in principle and are utilized in a case study: The impacts of a Chernobyl-like accident on the Swedish island of Gotland in the Baltic Sea are analyzed with regard to the acute consequences.

The use of the intervention principles found in international guidance (IAEA 91, ICRP 91), which can be summarized as the principles of **justification, optimization and avoidance of unacceptable doses**, are described.

How to handle more intangible factors of a psychological or political character is indicated.

Descriptors INIS/EDB

COST BENEFIT ANALYSIS; DECISION MAKING; EMERGENCY PLANS; OPTIMIZATION; PLANNING; RADIATION PROTECTION; REACTOR ACCIDENTS; REMEDIAL ACTION

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ISBN 87-550-1825-4
ISSN 0106-2840